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Demagnetizing Effect of Cylindrical Ni-Fe Thin Films

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Abstract

The squareness factor of cylindrical Ni-Fe thin films, which was derived from differential permeabilities on hysteresis loops of axial magnetization, deteriorated as the film thickness was increased and as the film length was shortened. The demagnetizing factor of such a thin film cylinder was estimated as a function of film thickness, film length, and substrate diameter. The squareness factor was little affected by the demagnetizing field if the demagnetizing factor was smaller than 10^{-4}, but the hysteresis rectangularity deteriorated as the demagnetizing field increased for the demagnetizing factor range larger than 10^{-4}. In addition, hysteresis shear correction and effects of demagnetizing field were considered.

I. Introduction

Permalloy (Ni 80-Fe 20) thin films have been developed for use as memory elements in high speed digital computers, since Blois(1) reported the preparation of soft ferromagnetic thin films having uniaxial anisotropy by vacuum deposition. Such thin films can also be produced by means of electrodeposition(2)(3)(4).

The differential permeabilities of cylindrical Ni-Fe thin films prepared by electrodeposition from a sulfate bath have been studied, and remarkable deterioration in their hysteresis loop squareness along the axial magnetization was observed as the film thickness was increased and as the film length was shortened. It is supposed that such a phenomenon was caused by the demagnetizing field upon the cylindrical thin film. Hence the demagnetizing factor for such a ferromagnet is to be estimated, and the demagnetizing effects are treated.

When thin ferromagnetic films are used as memory elements under destructive-readout operation, they should have rectangular hysteresis characteristics in order to assure high signal-to-noise ratio during each readout cycle. Therefore the geomerical dimensions of such a material are to be taken into consideration in the design of memory systems, so that each element is not affected by demagnetizing field which will be presented in this paper.

II. Experimental procedures

II. 1. Film preparation

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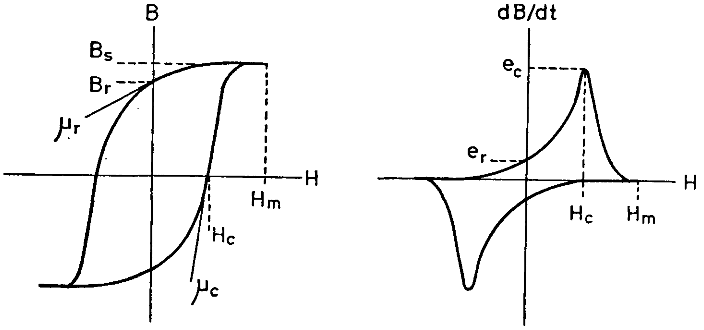
The Ni-Fe thin films were electroplated onto 1-mm copper wire substrates, which were degreased and chemically polished before electrodeposition. The plating bath was derived from Watts' bath, and had the following composition.

Nickel Sulfate	$NiSO_4 \cdot 6H_2O$	108 g/*l*
Ferrous Sulfate	$FeSO_4 \cdot 7H_2O$	25 g/*l*
Boric Acid	H_3BO_3	60 g/*l*

Boric acid was used as a buffer of acidity, and pH value in the plating bath was around 3.3. The plating tank (an approx. 500 cm^3 cylinder of bakelite) was immersed in a water bath, in order to keep a plating temperature constant within $30 \pm 0.5°C$. No agitation was superposed. A rolled, cylindrical Permalloy plate was used as an anode, and the copper wire substrate was placed as a cathode at the center. To obtain plating length of 10~50 mm on a copper wire substrate, its remaining area was coated with lacquer paint. The plating current was supplied from an adjustable current source, so as to keep a plating current density of 160 mA/cm^2 constant during each electrodeposition. These plating conditions yielded no deterioration phenomenon in the rate of flux reversal of electrodeposited Ni-Fe thin films as time elapsed after electrodeposition(5). The film thickness was estimated by weighing, and it was found that the current efficiency was approximately 93%. In addition, a solenoid coil was provided around the plating tank, and a DC current of 1 A through the solenoid produced an axial magnetic field of approximately 60 Oe. Therefore, the thin film specimens were expected to have longitudinal uniaxial anisotropy along the copper wire axis.

II. 2. Measurement technique

The conventional definition of squareness ratio(6) for a soft ferromagnetic material gives B_r/B_s on a hysteresis loop diagram of Fig. 1 (*a*), where B_s is saturation induction and B_r is residual induction. The precise measurement of such a squareness ratio is, however, very difficult because its value is settled near unity for a



(*a*) Hysteresis Loop Diagram.

(*b*) *H* vs *dB*/*dt* Trace Diagram.

Fig. 1. Hysteresis Loop and *H* vs *dB*/*dt* Trace Diagram.

square-loop material, and furthermore, because the hysteresis loop rectangularity is largely affected by the integrator characteristics in the display configulation. Therefore, in this experiment, the squareness factor SF is defined as a decibel value

$$SF = 20 \log (\mu_c/\mu_r), \tag{1}$$

where μ_c is the differential permeability dB/dH at $H=H_c$ (coercive field), and μ_r at remanent state (see Fig. 1. (*a*)). In addition, this squareness factor may correspond to the signal-to-noise ratio of a soft ferromagnetic material, when it is subjected to a memory application under the destructive readout operation.

By the application of sinusoidal external field H to a testing material, we obtain

$$H = H_m \sin \omega t, \tag{2}$$

$$\frac{dH}{dt} = \omega \sqrt{H_m^2 - H^2}, \tag{3}$$

where ω is angular frequency of the external driving field and H_m is the driving field amplitude. The instantaneous voltage induced from the testing material is expressed as

$$e = \frac{dB}{dt} \times N \times A \times 10^{-8}, \tag{4}$$

where N is the number of turns of a flux sense coil and A is the cross-sectional area of the testing material. Hence, combining the equation (3) with the equation (4), we obtain the expressions for the differential permeability μ_c at $H=H_c$ and μ_r at $H=0$ as

$$\mu_c = \frac{e \times 10^{-8}}{N \cdot A \cdot \omega \sqrt{H_m^2 - H_c^2}}, \tag{5}$$

$$\mu_r = \frac{e_r \times 10^{-8}}{N \cdot A \cdot \omega \cdot H_m}, \tag{6}$$

where e_c and e_r are instantaneous induced valtages at $H=H_c$ and $H=0$, respectively (see Fig. 1. (*b*)). In other words, the squareness factor of the equation (1) can be written in the following form.

$$SF = 20 \log \left\{ \frac{e_c}{e_r} \sqrt{\frac{1}{1-(H_c/H_m)^2}} \right\} \tag{7}$$

Fig. 2 shows a schematic diagram for displaying a H vs dB/dt trace of Fig. 1.(*b*) on an oscilloscope. A cylindrical Ni-Fe thin fiilm sample is coaxially placed in a drive solenoid D_1. through which a sinusoidal driving current of 1 kHz is delivered from an oscillator and a power amplifier. The resultant induced voltage e is picked up by a coaxial sense coil S_1, and applied to the vertical axis of the oscilloscope. On the other hand, the ocilloscope horizontal axis receives another voltage which is proportional to the external magnetizing field. The solenoid axis is aligned in the latitude direction so that the magnetic field of earth can be ignored. A pair of a drive solenoid D_2 and a coaxial sense coil S_2 has the same geometrical dimensions as those of above principal pair D_1 and S_1, so that the air flux component in the sense coil S_1 is cancelled out. Therefore, the induced voltage across S_1 and S_2 is proportional to the rate of net flux changes in the thin film sample under test.

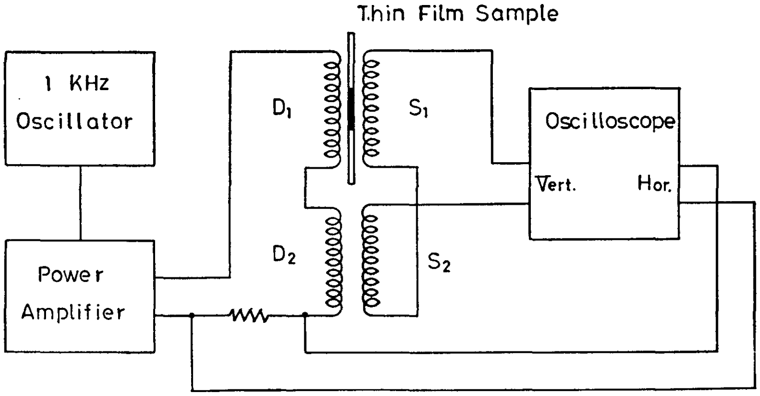
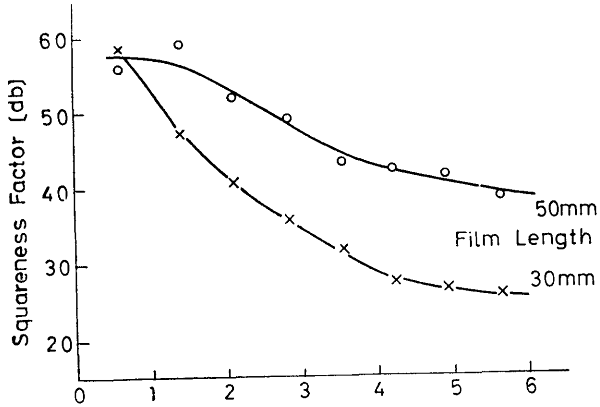


Fig. 2. Measurement System Diagram.

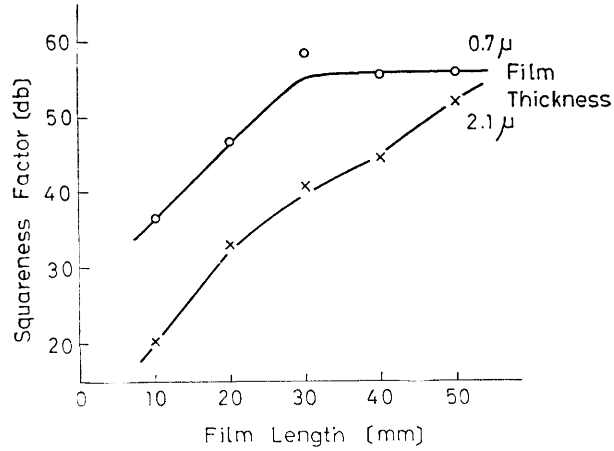
III. Results and discussions

III. 1. Effects of film thickness and film length

The effect of film thickness upon the squareness factor *SF* is shown in Fig. 3.(*a*) for different values of film length. It was observed that the squareness factor decreased as film thickness increased for each film length. It should be noted, however, that the average composition of elctrodeposited Ni-Fe thin film is thickness-dependent(7). Then the squareness deterioration of Fig. 3.(*a*) might be due to the compositional variation in the testing samples. On the other hand, Fig. 3. (*b*) shows the squareness factor *SF* as a function of film length, in which the film thickness is used as a parameter. It was verified, from the result of Fig. 3. (*b*), that the squareness factor was also decreased as the film length was shortened under the condition of constant film thickness. Therefore, it was supposed that these deteriorations in the squareness of the Ni-Fe thin film hysteresis characteristics were chiefly caused by demagnetizing fields upon the thin film sample, since the demagnetizing factor in a rectangular prism is increased as a prism dimension perpendicular to the applied field is lengthened, and also as that parallel to the applied field is shortened(8). The former case corresponds to the thickness effect of Fig. 3.(*a*), and the latter case to the length effect of Fig. 3. (*b*).



(*a*) Thickness Effect.



(*b*) Length Effect.

Fig. 3. Effects of Film Thickness and Film Length on Squareness Factor.

III. 2. Demagnetizing effect

Although it is well known that the surface divergence of the magnetization vector gives rise to a magnetic field, usually termed "demagnetizing field"(8), and that the demagnetizing factor of a magnetic material is defined as the ratio of the magnetization and the demagnetizing field(9), the precise magnitude of the demagnetizing factor for arbitrary tubes could not be found in the literature. If we assume, however, that the demagnetizing field H' in a thin film cylinder with inner diameter d, outer diameter $d+t$, and length l, is estimated as

$$H'=H_1'-H_2', \tag{8}$$

an approximate expression for its demagnetizing factor can be calculated in the following way ; in above equation (8), H_1' being the demagnetizing field in a prolate ellipsoid of revolution with short axis diameter $d+t$ and long axis diameter l, while H_2' being that with short axis diameter d and long axis diameter l.

The demagnetizing factor N for a prolate ellipsoid of revolution with axes $a=mc$ and $b=c$, which is magnetized parallel to the long axis, a, is given by the following formula(9).

$$N=\frac{4\pi}{m^2-1}\left\{\frac{m}{2\sqrt{m^2-1}}\ln\left(\frac{m+\sqrt{m^2-1}}{m-\sqrt{m^2-1}}\right)-1\right\} \tag{9}$$

Hence the demagnetizing factor N' for a thin film cylinder is approximated as

$$N'\fallingdotseq\frac{4\pi a}{b}\left\{4\left(1+\frac{3}{b^2}\right)\ln 2b-\left(6+\frac{13}{b^2}\right)\right\}, \tag{10}$$

where $a=t/l\ll1$, $b=l/d\gg1$, l is the fiilm length, t is the film thickness, and d is the diameter of the copper wire substrate.

A relationship between the squareness factor SF and the approximated demagnetizing factor N' is plotted in Fig. 4 for Ni-Fe thin film samples with various values of film length and film thickness. A clear correlation was found between the squareness factor and the demagnetizing factor, as was expected from the results of Fig. 3.(*a*) and Fig. 3. (*b*). If the demagnetizing factor N' was smaller than 10^{-4} (corresponding to the demagnetizing field H' of approximately 0.1 Oe), on the other hand, the squareness factor was independent on N'. It suggested, therefore, that the demagnetizing factor should be smaller than 10^{-4} for the production of a cylindrical thin film ferromagnet with good hysteresis rectangularity.

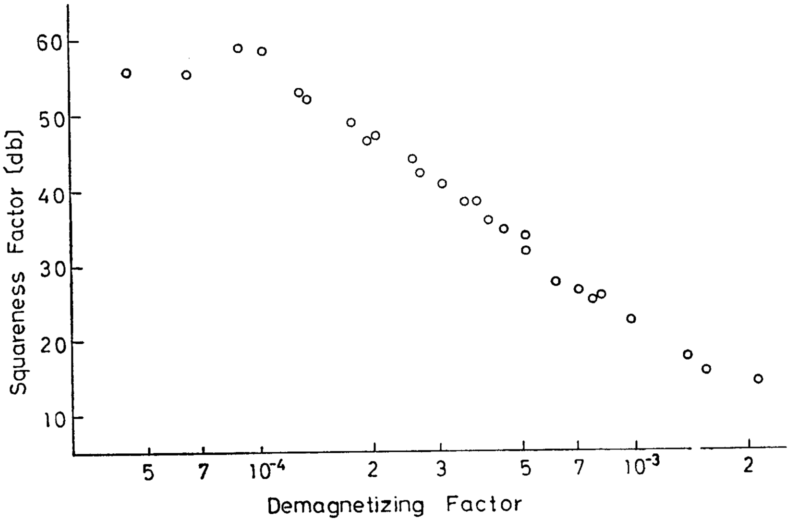


Fig. 4. Effect of Demagnetizing Factor on Squareness Factor.

III. 3. Hysteresis shear correction

The differential permeability data were obtained from sheared hysteresis loops, and the sheared squareness factor should be corrected by the knowledge of demagnetizing field. The corrected differential permeability μ_c' at $H=H_c$ can be written as

$$\mu_c'=\frac{4\pi\mu_c}{4\pi-N'\mu_c}\,. \tag{11}$$

On the other hand, by the employment of a simple assumption that $\mu=0$ at $|H|\geq H_c$ and the magnetic induction is a quadratic function of the external field H in the neighbourhood of the remanent state, the corrected differential permeability μ_r' at $H=0$ is given by the expression

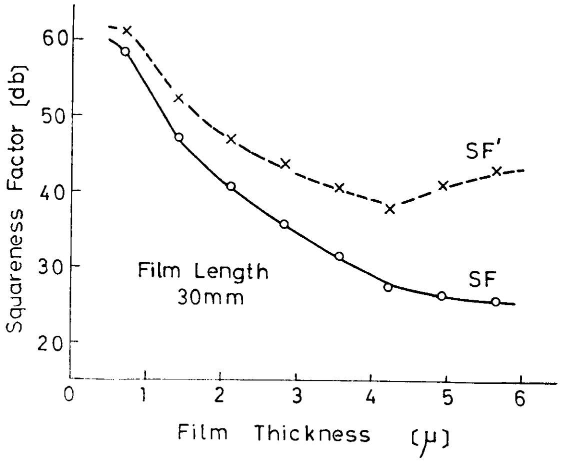
$$\mu_r'=\mu_r(1-H'/H_c), \tag{12}$$

which is valid only for demagnetizing fields H' smaller than the coercive field H_c.

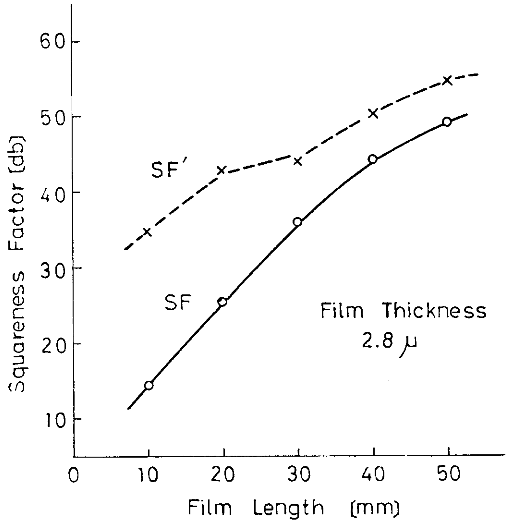
The shear corrections for the squareness factor due to the demagnetizing field are illustrated in Fig. 5, in which the measured squareness factor SF is plotted by solid lines, and the corrected squareness factor SF' calculated by the following equation is plotted by dashed lines.

$$SF'=20\log(\mu_c'/\mu_r') \tag{13}$$

The deteriorations in the measured squareness factor were partly recovered by the hysteresis shear correction. Although above assumption was simple enough and hence the shear corrections were not precise, the uncorrected part might be due to the increrse of easy axis dispersion and the nucleation of reverse domains(10) caused by the demagnetizing field.



(a) Thickness Effect.



(*b*) Length Effect.

Fig. 5. Hysteresis Shear Corrections due to Demagnetizing Field.

IV. Conclusions

The squareness factor of cylindrical Ni-Fe thin films, which was derived from differential permeabilities on hysteresis loops of axial magnetization, was largely dependent upon the film thickness and the film length. With the approximation of the thin film cylinder to be a prolate ellipsoidal shell of revolution its demagnetizing factor was calculated as a function of film thickness, film length, and substrate diameter. The squareness factor was strongly correlated to the demagnetizing factor. Namely, the hysteresis loop rectangularity deteriorated as the demagnetizing field increased for the demagnetizing factor larger than 10^{-4}. Under the demagnetizing factor smaller than 10^{-4}, however, the squareness factor was not affected by the demagnetizing field. It was found that the deteriorations in the measured squareness factor were partly due to the shear of the hysteresis loop. Hence the uncorrected part might be due to the increase of easy axis dispersion and the nucleation of reverse domains caused by the demagnetizing field.

V. Acknowledgement

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