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Magnetic Properties and Magnetoimpedance Effect in Mumetal Thin Films

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The dependence of the magnetoimpedance effect (MI) on magnetic properties has been investigated in mumetal thin films prepared by rf magnetron sputtering. Coercivity of thin films prepared at 400 W was about 0.4 Oe, and the magnetic anisotropy field of films deposited under a uniaxial magnetic field decreased with increasing film thickness. The saturation magnetization of mumetal films increased with rising input power and thickness, and was smaller than that of permalloy films. Transverse incremental Permeability (TPR) of films of 1 μm thick increased with increasing effective permeability. The magneto impedance ratio (MIR) was proportional to TPR in films 1 μm thick but in spite of lower effective permeability at higher thicknesses, MIR increased due to skin effect. The height of the double peaks in the MIR curves decreased with decreasing anisotropy and thickness. The maximum MIR value for a 4 μm thick 75 % at 36.5 MHz.

1. Introduction

Recently, large and sensitive changes in magnetoimpedance (MI) have been studied in nearly zero magnetostrictive amorphous wires, ribbons, and films, because of possible novel applications in magnetic sensors. The MI effect can be explained as a result of the transverse magnetization with respect to the current direction through the sample and the skin effect of an ac current, and is observed only in very soft magnetic materials [1, 2]. Because an ac current tends to concentrate near the surface of a conductor, the impedance Z changes with the current distribution and the shape of the conductor. Also, the MI effect is proportional to $(\omega\mu_\varphi)^{1/2}$ where μ_φ is the transverse magnetic permeability and depends on the strength of the external magnetic field and on the magnetic anisotropy. The change in incremental transverse permeability [3] has brought much interest in the physical understanding of as well as in MI applications for magnetic recording heads and magnetic sensors. The incremental permeability is defined as the changing induction divided by the cyclically changing magnetic field when the dc magnetic field acting on a specimen is maintained constant and an additional ac field is alternated cyclically between two limiting values [3]. The mumetal thin films in this study are composed of a soft magnetic material, permalloy (NiFe), with additives Mo and Cu [4]. In general, mumetal thin films have lower coercivity, saturation magnetization, and magnetic anisotropy than permalloy thin films, due to low local anisotropy and structural constants [5, 6]. In this study, the MI effect in mumetal thin films of varying thinkness was investigated in conjunction with magnetic properties such as the effective permeability and the transverse incremental permeability.

2. Experimental

Mumetal thin films with a diameter of 17 mm and thicknesses of 1~4 μm were deposited on a glass substrate (Corning 7059) by rf magnetron sputtering under an Ar gas pressure of 1×10^{-3} Torr. RF input power was varied in the range of 100 to 400 W. In order to induce in-plane magnetic anisotropy, the deposition was performed in a dc magnetic field of about 300 Oe parallel to the film plane. The composition of the films was analyzed by EPMA (Electron Prove Micro Analysis) and AES (Auger Electron Spectroscopy). The magnetic easy axis and the magnetic properties such as coercivity (H_c) and saturation magnetization (M_s) were measured using a vibrating sample magnetometer (VSM) designed for soft magnetic materials. The effective permeability (μ_{eff}) along the magnetic hard axis was measured at 2 MHz by the ferrite core method [7]. The MI effect was investigated with a strip type sample of length 15 mm and width 2 mm, prepared lithographic method. A schematic diagram of the geometry of the MI measurement is shown in Fig. 1. The short (width) direction of the samples was parallel to the magnetic easy axis and an external magnetic field was applied parallel to the long axis. The frequency of the ac current was from 0.5 to 40.5 MHz, and was held at 10 mA in all measurements. The magnetoimpedance ratio (MIR) can be defined as MIR=$|\Delta Z(H)/$

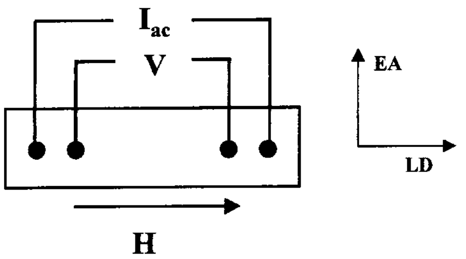


Fig. 1. Schematic diagram of measurement system for MI effect measured by four point probe. EA is easy axis and width direction, and LD is length direction. The AC magnetic field generated by I_{ac} acts parallel to EA.

$Z(H_{max})=|[Z(H)-Z(H_{max})]/Z(H_{max})|$. H_{max}, an external magnetic field sufficient to saturate the magnetoimpedance, was taken as 120 Oe in this study. We also designed a measurement system for the transverse incremental permeability ratio (TPR). A computer controlled rf signal generator driving power amplifier was connected to the primary coil in series with a resistor for monitoring ac drive current, and the voltage induced in a secondary coil was measured using digital multimeters (DMM) with RF/V probes. The frequency of the ac current was maintained at 2 MHz for the TPR measurement, in which an external magnetic field is perpendicular to the primary and the secondary coils. In this study, TPR was only measured parallel to the easy axis.

3. Results and Discussion

The magnetic properties and compositions of the mumetal thin films are shown, together with the sputtering conditions, in Table 1 and 2. With increasing of rf input power, the Ni content increased but the Fe content decreased, whereas the Mo and Cu contents were not significantly changed. Saturation magnetization and effective permeability increased with rising rf input power. However, as the thickness of samples increased, the saturation magnetization increased but the effective permeability decreased. The saturation magnetization of mumetal films is smaller than that of permalloy, which attributed to a highly disordered structure which gives rise to high internal stress caused by the added Mo and Cu. [4]. Coercivity decreased with increasing input power but remained about 0.4 Oe at all thicknesses. The magnetic properties of mumetal thin films prepared by sputtering were similar to those reported by Collins *et al.* [4], which can be attributed to optimum composition and the small structure factor from the diffusion of the high energy incident elements [8]. Also, the decrease of effective permeability with increasing thicknesses can be explained by the fact that the thicker films have high magnetization dispersion [9], demagnetizing field [10] and large grain size [11].

Table 1. Magnetic properties of mumetal films with thicknesses of 1 μm fabricated at various rf input powers

Input power (W)	Composition (wt%)	Coercivity (Oe)	Saturation magnetization (emu/cm^3)	Effective permeability
100	$Ni_{80.2}Fe_{14.7}Cu_{2.2}Mo_{2.9}$	0.75	380	1800
200	$Ni_{80.5}Fe_{14.4}Cu_{2.2}Mo_{2.9}$	0.62	410	2250
300	$Ni_{80.8}Fe_{14.3}Cu_{2.1}Mo_{2.8}$	0.53	460	2850
400	$Ni_{81.1}Fe_{14.2}Cu_{1.9}Mo_{2.8}$	0.35	480	3050

Table 2. Magnetic properties of mumetal films with various thicknesses fabricated at 400 W and 1 mTorr

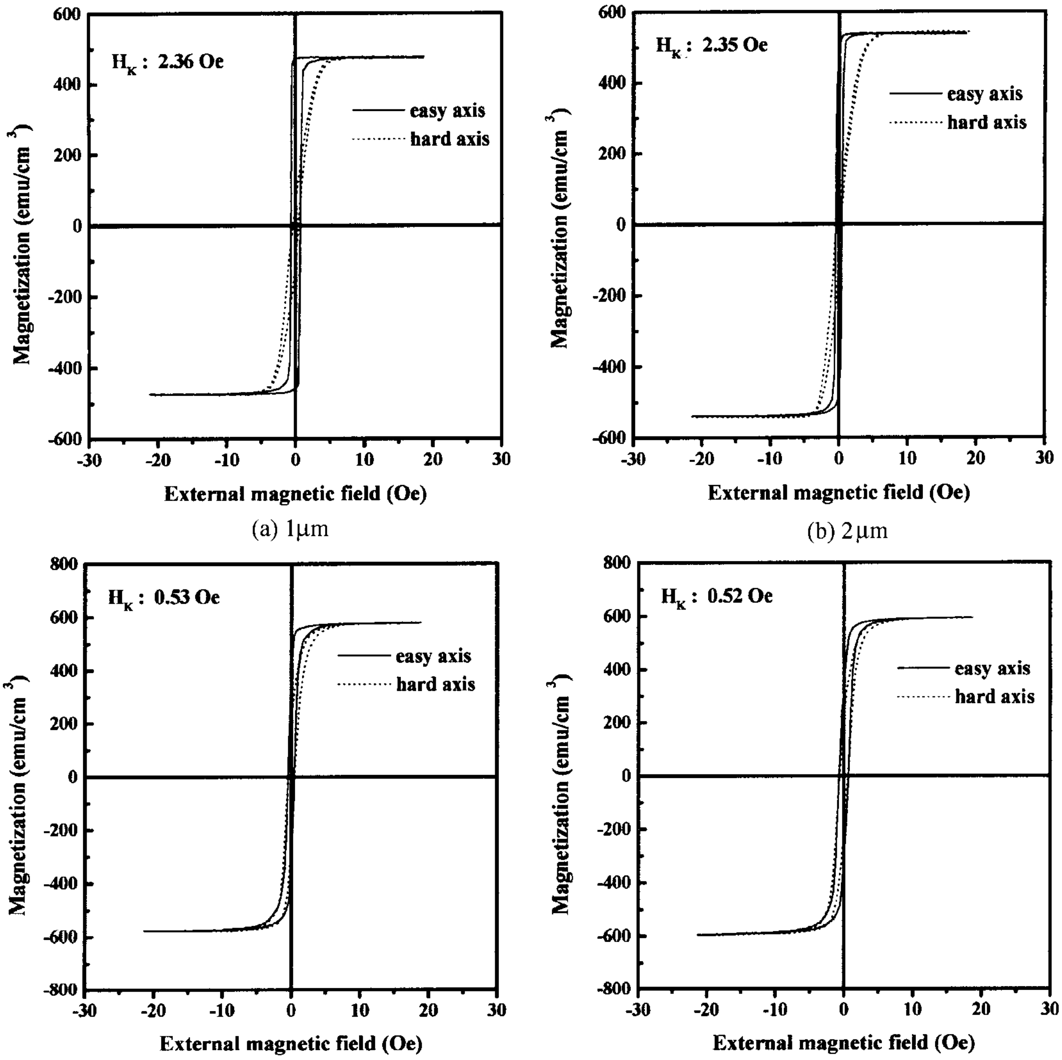
Film thickness (μm)	Composition (wt%)	Coercivity (Oe)	Saturation magnetization (emu/cm^3)	Effective permeability
1	$Ni_{81.1}Fe_{14.2}Cu_{1.9}Mo_{2.8}$	0.35	480	3050
2	–	0.39	540	2200
3	–	0.43	580	1500
4	–	0.39	600	1250

M-H hysteresis loops of circular samples with various thicknesses are shown in Fig. 2. The film with thickness of 1 μm exhibited an obvious difference between the hysteresis loops of the easy axis and the hard axis, whereas the films with thicknesses over approximately 3 μm did not. The magnetic anisotropy fields of films with thicknesses of 1 μm and 3 μm were 2.36 Oe and 0.53 Oe, respectively. The decrease of magnetic anisotropy field with increasing thicknesses is attributed to the increase of demagnetizing field and of grain size [12].

Figure 3 shows TPR curves measured in the easy axis direction in films with various values of effective permeability. The TPR curves showed a double peak pattern for all samples, with higher TPR values at larger values of effective permeability. The peak patterns in the TPR curves are strongly dependent on the direction of magnetization parallel to an ac magnetic field generated by an ac drive current. However, in case of hard axis, the peak patterns were observed a single peak.

Figure 4 shows the TPR curves measured along the easy axis in thin films with various thicknesses. For film thicknesses of 1, 3 and 4 μm, the maximum values of TPR were in 24, 27 and 33 %, respectively. However, the values measured at zero external magnetic field were about half maximum value. This reduction is identical with the data of M-H hysteresis loop and other results [13, 14] on magnetic anisotropy in mumetal thin films.

The MIR curves measured on films 1 to 4 μm thick are shown in Fig. 5. The films had strip geometry and the frequency of measurement was 36.5 MHz. The MIR was directly proportional to the thickness of films. The maximum value of MIR was about 75 % for a film thickness of 4 μm. This value is much larger than previous reported values [15, 16] because of the magnetic softness of our thin films, indicates by low coercivity, and high effective permeability and transverse incremental permeability.



(a) 1μm

(b) 2μm

(c) 3μm

(d) 4μm

Fig. 2. M-H hysteresis curves measured parallel and perpendicular to easy axis in mumetal films with thicknesses (a) 1 μm, (b) 2 μm, (c) 3 μm, (4) 4 μm.

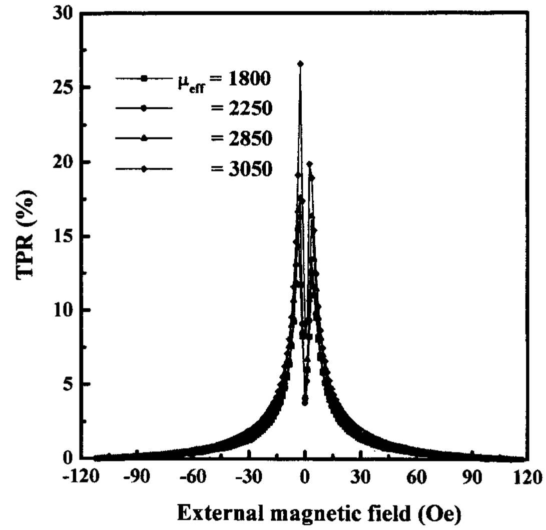


Fig. 3. TPR curves measured at 2 MHz as a function of effective permeabilities.

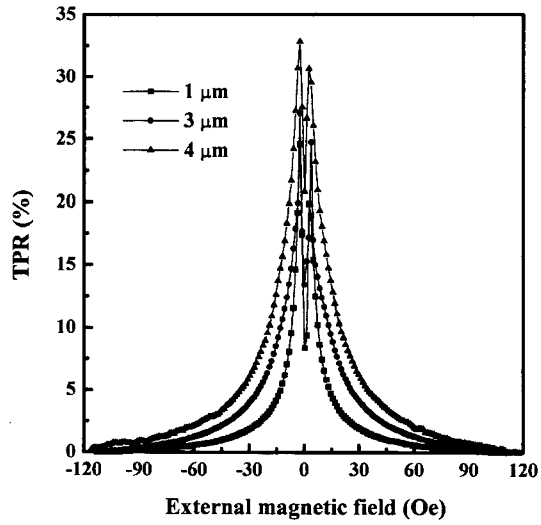


Fig. 4. TPR curves measured at 2 MHz as a function of mumetal film thickness.

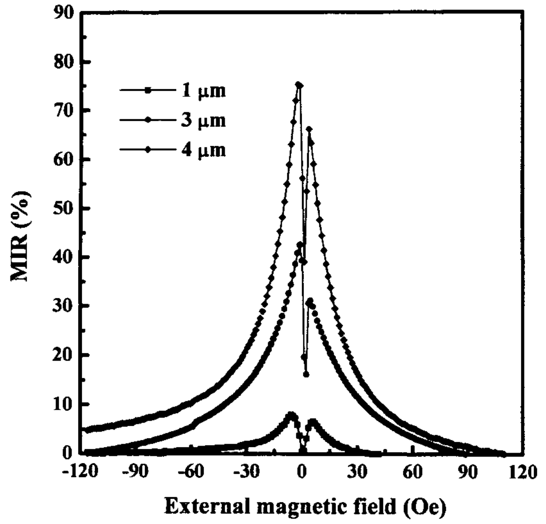


Fig. 5. MIR curves measured at 36.5 MHz as a function of mumetal film thickness.

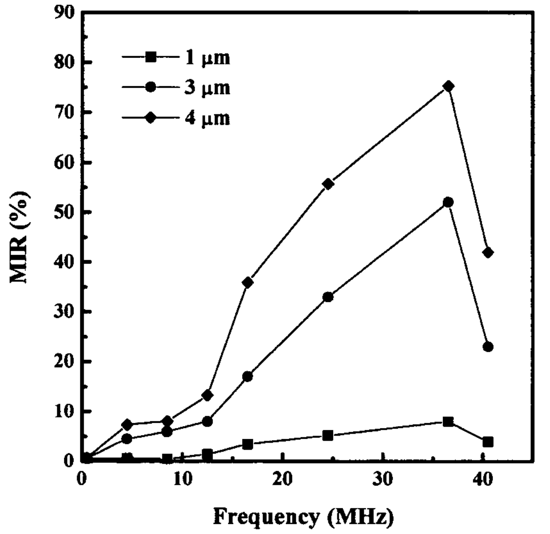


Fig. 6. Frequency dependence of MIR for various mumetal film thickness.

The frequency dependence of the MI effect exhibited typical behavior [2]. As clearly shown in Fig. 6, the MIR increased up to 36.5 MHz and then decreased at higher frequency [4]. The frequency dependence is related to the motion of domain walls and the rotation of magnetic moments. The MI effect is proportional to $(\omega\mu_\psi)^{1/2}$ where μ_ψ results from domain wall permeability at low frequency and rotational permeability at high frequency. Therefore, the increase of the MI effect with increasing frequencies can be explained in term of the change of the dominant factor from the motion of domain walls to the rotation of the magnetic moment, with increasing frequency [1].

4. Conclusion

The relationship between the MI effect and magnetic properties of mumetal thin films prepared by rf magnetron sputtering has been investigated. TPR was directly proportional to the effective permeability in mumetal thin films with the same thickness, and the values increased with increasing thickness. MIR curves were very similar to TPR curves, because the transverse incremental permeability is directly related to the MI effect. Also, MIR increased up to a frequency of 36.5 MHz and then decreased with increasing frequency. The maximum value of MIR was about 75 % for a film thickness of 4 μm.

Acknowledgments

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