

Effects of Heat Treatments on Magnetoimpedance of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ Ribbons

Pongsakorn Jantaratana* and Saisunee Pasuksan

ABSTRACT

The magnetoimpedance effect in $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbons was studied as a function of the frequency of the driving current and the static magnetic field. The as-cast sample exhibited single peak magnetoimpedance with small hysteresis in the low magnetic field regime. The conventional furnace annealing led to magnetic hardening and a decrease in the magnetoimpedance ratio. However, furnace annealing also induced transverse magnetic anisotropy and increased the magnetic field sensitivity. The maximum field sensitivity of 6%/Oe for the as-cast sample increased to more than 14 %/Oe after being annealed at 200°C. The magnetoimpedance of the samples can be explained by the frequency of the current and magnetic field dependence on the transverse magnetic permeability of the soft ferromagnetic conductor.

Key words: annealing, magnetic anisotropy, magnetic permeability, magnetoimpedance, skin effect

INTRODUCTION

Magnetoimpedance (MI) is a change of the electrical impedance in soft ferromagnetic conductors as a response to an applied static magnetic field, when high frequency alternating current flows through the conductor. The cross-sectional current density over the conductor depends on the frequency of the current, the magnetic and the electrical properties of the conductor. In a high frequency regime, the current density is at a maximum at the surface and decreases toward the center corresponding to the skin effect. The depth at which the current density reduces to 37% of that at the surface is called the skin depth (δ) and can be written as:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

where:

f is the frequency of the AC current along the conductor

σ is the electrical conductivity

μ is the transverse or circumferential magnetic permeability of the conductor.

The MI effect was first reported by Harrison *et al.* (1935) with an MI ratio of about 17%. To the present time, MI ratios in the order of several hundred percent have been observed. This effect has been extensively studied over the last decade, due to its direct application in highly-sensitive magnetic sensors (Takayama *et al.*, 1999; Shen *et al.*, 2000; Kurlyandskaya *et al.*, 2003).

Physically, the MI effect is a strong modification in the transverse or circumferential permeability of the conductor caused by a static magnetic field. Owing to the high magnetic

permeability of soft ferromagnetic materials, the application of a magnetic field along the sample axis changes the skin depth through a modification of the permeability which results in a change in impedance. Thus, for a ferromagnetic conductor, the magnetic field dependence on the permeability is the main factor that controls the MI behavior. However, the physical properties of ferromagnetic materials can be modified by means of proper heat treatments. By choosing an appropriate material and performing specific thermal treatments, it is possible to tailor special impedance responses. The effect of heat treatments has been reported for conventional furnace annealing (Brunetti *et al.*, 2001; Tiberto *et al.*, 2002), annealing under tensile stress (Kurlyandskaya *et al.*, 1999; Coisson *et al.*, 2003) and current annealing (Pirota *et al.*, 2001). In this paper, the MI effect of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbons is studied as a function of the frequency of the driving current and the applied magnetic field. The effects of annealing temperature on MI are also discussed.

MATERIALS AND METHODS

The MI effect of a ribbon-like $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ (Metglas™ 2826MB) as used in anti-theft markers was studied. Open-air annealing was performed using a box furnace. The samples were annealed at four different maximum annealing temperatures: 200, 250, 300 and 350°C, with a heating rate of 0.5°C/min. The maximum temperature was held for 1.5 h and then cooled down at a cooling rate of 0.5°C/min. For the MI measurement, the 30 mm × 6 mm × 2.5 μm samples were placed in a longitudinal, static magnetic field H , supplied by a pair of Helmholtz coils. The impedance Z of the samples was measured using a precision LCR meter and the AC current was fixed at 10 mA. The open and short compensation functions of the LCR meter were used to eliminate measurement errors due to the fixture and extension cables. All measurements

were carried out at room temperature.

The MI ratio ($\Delta Z/Z$) is defined as:

$$\frac{\Delta Z}{Z} (\%) = \left(\frac{Z_H - Z_{H_{\max}}}{Z_{H_{\max}}} \right) \times 100$$

where:

Z_H and $Z_{H_{\max}}$ represent the impedance in magnetic field H and in the maximum magnetic field, respectively.

The magnetic field sensitivity (S) of the MI effect is defined as:

$$S(\% / \text{Oe}) = \frac{(\Delta Z / Z)}{\Delta H}$$

where:

ΔH is the changing magnetic field ($\Delta H = 0.45$ Oe).

RESULTS AND DISCUSSION

The dependence of the impedance on the frequency of the AC current in the as-cast sample is shown in Figure 1. For a frequency regime lower than 100 kHz, the zero field impedance is relatively constant, since the skin effect is weak and the current almost flows through the entire cross

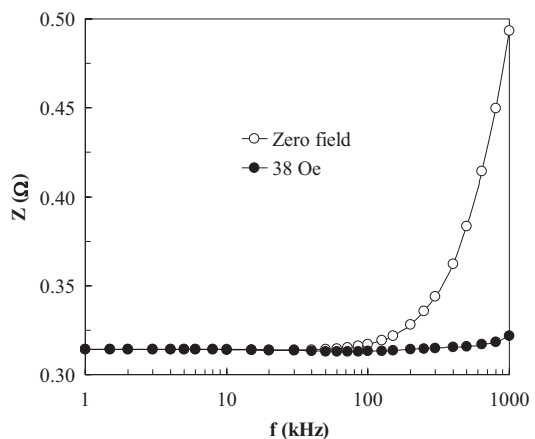


Figure 1 Frequency dependence of the impedance in an applied DC magnetic field of zero and 38 Oe for a 30 mm × 6 mm × 2.5 μm sample.

section. Above a critical frequency of 150 kHz, the skin depth becomes smaller than one half of the sample thickness ($h = 2.5 \mu\text{m}$) and the zero field impedance is very sensitive to the frequency. Under a longitudinal magnetic field of 38 Oe, the impedance is relatively constant with an increasing frequency from 1 kHz to 1 MHz. The insensitivity to the frequency of the impedance under the magnetic field can be explained by the skin effect. When an external DC magnetic field is applied in the longitudinal direction, the transverse permeability decreases and approaches saturation and the skin depth therefore becomes comparable to half the thickness at a frequency higher than 1 MHz. By neglecting the current flow deeper than the skin depth, the critical frequency can be estimated from the condition $\delta = h/2$.

In Figure 2, the dependence of the MI ratio on the magnetic field H is shown at a frequency of 1 MHz. The longitudinal, cyclic magnetic field was applied by the Helmholtz coils using a step-like changing current. The maximum 63 % MI ratio was observed in the as-cast sample. The MI curve shows a typical single peak during a half cycle of the applied magnetic field. The monotonic decrease of the MI ratio reflects the axial magnetic anisotropy existing in the sample (Usov *et al.*, 1998). When the magnetic field was

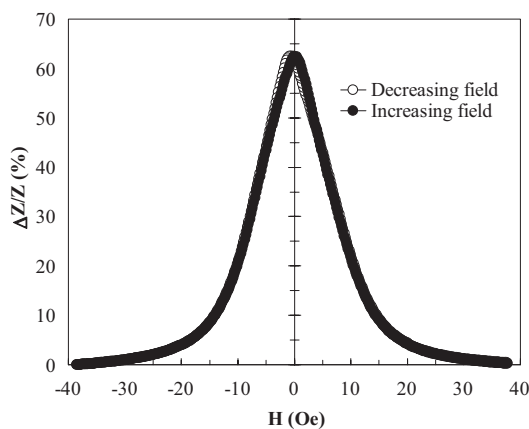


Figure 2 Field dependence of MI ratio at a frequency of 1 MHz for as-cast sample.

applied in the easy direction (longitudinal), the magnetization rotation dominated over the transverse magnetization process. The transverse permeability and the impedance therefore decreased and finally reached a very low constant value. Since the zero field impedance was relatively constant, the MI curve therefore changed in the same fashion as the impedance under an applied magnetic field. The maximum magnetic field sensitivity of 6%/Oe was observed in the low field regime. The sensitivity was low at high field when the transverse permeability approached saturation. With a cyclic magnetic field smaller than 4 Oe, the MI curve exhibited small hysteresis.

The dependence of the impedance on the magnetic field, measured at a fixed AC current of 10 mA and a frequency of 1 MHz is shown in Figure 3 for samples with various annealing temperatures. The MI curves show two asymmetric peaks each while there is a decreasing or increasing magnetic field. For the decreasing field, the peak in the negative-field region was smaller than that of the positive field region, but the opposite tendency was observed for the increasing field. Since the field dependence of MI is mainly determined by the type of magnetic anisotropy (Usov *et al.*, 1998), it is noted that the transverse anisotropy field was induced during the annealing process. By increasing the externally-applied magnetic field along the hard axis (in the longitudinal direction), the magnetization in each domain rotated towards the easy axis. Consequently, the transverse permeability and thus the impedance were increased. Maximum permeability was obtained when an externally-applied field balanced the transversal anisotropy field and the impedance reached its maximum value. With a further increase in the applied magnetic field, the magnetization rotation dominated the transverse magnetization process. The transverse permeability and the impedance therefore decreased and finally reached a very low

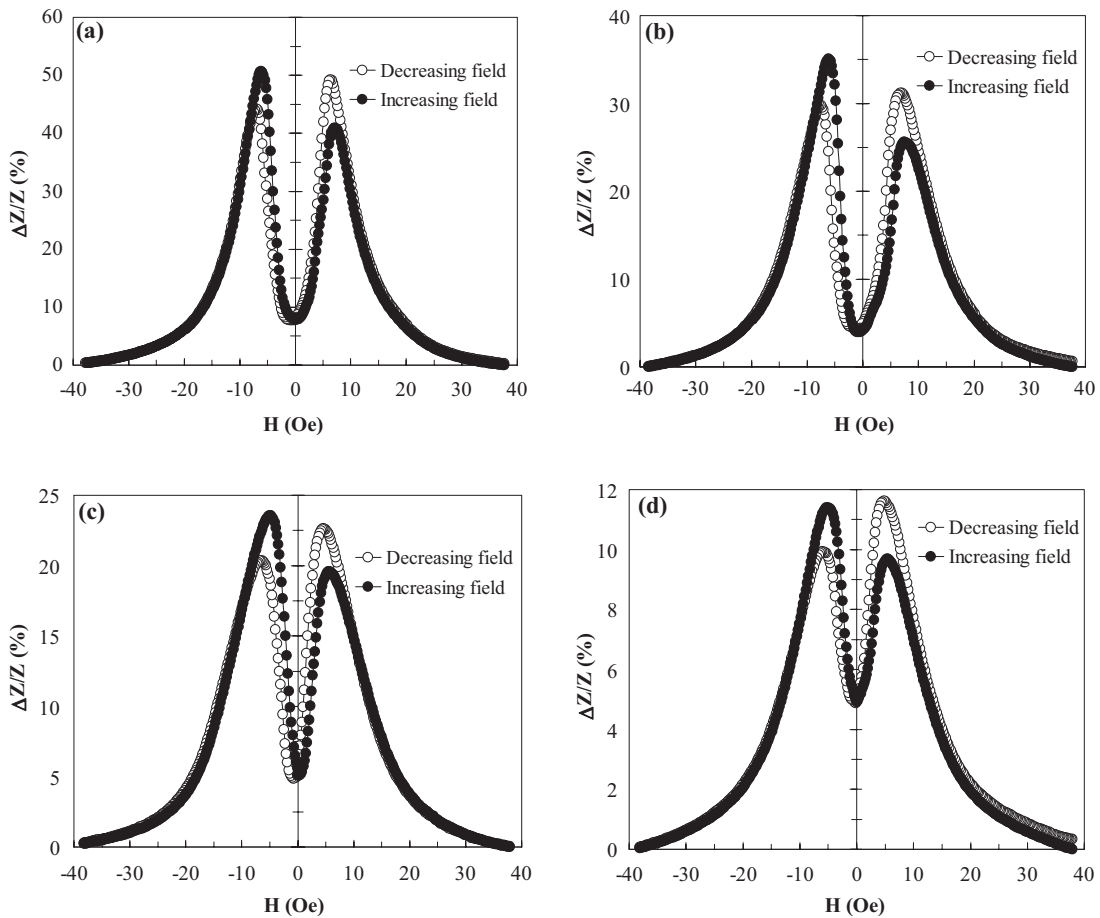


Figure 3 Field dependence of MI ratio at a frequency of 1 MHz for samples with various annealing temperatures, (a) 200°C, (b) 250°C, (c) 300°C and (d) 350°C.

value. Thus, if the external magnetic field were swept both parallel and antiparallel to the sample axis, the field dependence of the impedance or MI would display two peaks as seen in Figure 3. With increasing annealing temperature, the maximum MI ratio and field sensitivity decreased. However, the field sensitivity of samples with annealing temperatures of 200°C, 250°C and 300°C was larger than that of the as-cast sample.

CONCLUSIONS

The MI ratio of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbons depended on the applied magnetic field, the

frequency of AC current and the annealing temperature. The MI ratio of an as-cast sample monotonically decreased with an increase in external magnetic field. This monotonic decay indicated longitudinal anisotropy. The effects of conventional furnace annealing on MI were studied. It was found that the maximum MI ratio and the sensitivity of the annealed samples decreased with increasing annealing temperature. However, the samples annealed at 200°C, 250°C and 300°C exhibited higher sensitivity compared to the as-cast sample. Transverse anisotropy was also induced in the annealed samples. Finally, the conventional furnace annealing technique can be

used to improve the field sensitivity of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbons.

LITERATURE CITED

- Brunetti, L., M. Coisson, P. Tiberto, F. Vinai, H. Chiriac and F. Borza. 2001. Comparison between magnetoimpedance properties of $\text{Fe}_{73.5}\text{Cu}_3\text{Nb}_1\text{Si}_{13.5}\text{B}_9$ melt-spun and glass-covered wires. **Sensor. Actuat. A-Phys.** 91: 203–206.
- Coisson, M., P. Tiberto, F. Vinai and S. N. Kane. 2003. Influence of stress-annealing on magneto-transport properties in Co-based amorphous ribbons. **Sensor Actuat. A-Phys.** 106: 199–202.
- Kurlyandskaya, G. V., M. L. Sánchez, B. Hernando, V. M. Prida, P. Gorria and M. Tejedor. 2003. Giant magnetoimpedance-based sensitive element as a model for biosensors. **Appl. Phys. Lett.** 82: 3053–3055.
- Kurlyandskaya, G. V., M. Vázquez, J. L. Muñoz, D. Garcia and J. McCord. 1999. Effect of induced magnetic anisotropy and domain structure features on magnetoimpedance in stress annealed Co-rich amorphous ribbons. **J. Magn. Magn. Mater.** 196–197: 259–261.
- Harrison, E. P., G. L. Turney and H. Rowe. 1935. Electrical properties of wires of high permeability. **Nature.** 135: 961–961.
- Pirota, K. R., L. Kraus, H. Chiriac and M. Knobel. 2001. Magnetostriction and GMI in Joule-heated CoFeSiB glass-covered microwires. **J. Magn. Magn. Mater.** 226–230: 730–732.
- Shen, L. P., K. Mohri, T. Uchiyama and Y. Honkura. 2000. Sensitive acceleration sensor using amorphous wire SI element combined with CMOS IC multi-vibrator for environmental sensing. **IEEE Trans. Magn.** 36: 3667–3669.
- Takayama, A., T. Umehara, A. Yuguchi and H. Kato. 1999. Integrated thin film magnetoimpedance sensor head using plating process. **IEEE Trans. Magn.** 35: 3643–3645.
- Tiberto, P., M. Coisson, F. Vinai and S. N. Kane. 2002. Effect of annealing on high-frequency magnetoimpedance in $\text{Co}_{83.2}\text{Mn}_{7.6}\text{Si}_{5.9}\text{B}_{3.3}$ glass-coated micro-wires. **IEEE Trans. Magn.** 38: 3093–3095.
- Usov, N. A., A. S. Antonov and A. N. Lagar'kov. 1998. Theory of giant magnetoimpedance effect in amorphous wires with different type of magnetic anisotropy. **J. Magn. Magn. Mater.** 185: 159–173.