

## Annealing Effect of Local Anisotropy Field in Amorphous $\text{Co}_{66}\text{Fe}_4\text{Ni}_1\text{B}_{14}\text{Si}_{15}$ Ribbon

C. G. Kim, K. J. Jang, M. H. Jeong, S. S. Yoon\* and S. C. Yu\*\*

*Department of Physics, SunMoon Univ., Chungnam 336-840, Korea*

*\*Department of Physics, Andong Univ., Kyung-book 760-749, Korea*

*\*\*Department of Physics, Chungbuk Nat'l Univ., Cheongju 361-763, Korea*

(Received 10 November 1998)

The magneto-impedance (MI) has been measured in the annealed  $\text{Co}_{66}\text{Fe}_4\text{Ni}_1\text{B}_{14}\text{Si}_{15}$  amorphous ribbon for the evaluation of anisotropy field. MI at the frequency of 10 MHz is related to the transverse permeability from rotational magnetization depending on the local anisotropy field. MI varies sensitively with the annealing temperature, reflecting the change of anisotropy field distribution. The local anisotropy fields evaluated from MI profiles are discussed in terms of the magnetic softness and microstructural change by the annealing.

### 1. Introduction

A lot of works on the magneto-impedance (MI) has been studied in the soft magnetic Co-, Fe-based amorphous and nanocrystalline alloys for the sensitive magnetic sensors, where MI is understood as the effect of magnetic field on transverse permeability to ac current direction [1, 2]. MI profile during a half cycle of magnetization for low operating frequency shows a broad maximum around zero field due to the dominant contribution from wall motion. As the frequency increases over a few hundreds kHz, the dip in the MI profile appears, showing two peaks split at the zero field. In this frequency range, the wall motion begins to be damped, in turns, the effect of rotational magnetization on MI is comparable to that of wall motion. The dip becomes profound as the frequency increases, being ascribed for by the fact that the rotational magnetization is responsible for MI profile.

It has been known that the effective anisotropy field plays significant role in MI where rotational magnetization is major contribution to the transverse permeability [1, 3]. In present work we investigate the variation of local anisotropy field in  $\text{Co}_{66}\text{Fe}_4\text{Ni}_1\text{B}_{14}\text{Si}_{15}$  amorphous ribbon annealed at different temperatures, determined by analysis of MI profiles near the zero field.

### 2. Theoretical Background

The magneto-impedance (MI) of magnetic materials in ribbon geometry under a longitudinal probe current  $I=I_0 e^{j\omega t}$  in high frequency range, at which the skin depth becomes

inferior to the sample thickness, can be written as [1]:

$$Z(\omega, H) \propto \sqrt{\omega \mu_t(\omega, H)} \quad (1)$$

where  $H$  is the longitudinal dc field and  $\mu_t$  is transverse magnetic permeability which consists of two parts of contributions:

$$\mu_t(\omega, H) = \mu_{dw}(\omega, H) + \mu_{rot}(\omega, H) \quad (2)$$

where  $\mu_{dw}$  and  $\mu_{rot}$  are transverse permeability originating from domain wall motion and magnetization rotation, respectively. The permeability from wall motion is dominant over the rotational magnetization in the low frequency range. As the frequency increases over a few MHz in the Co-based amorphous samples, the wall motion is nearly damped [4], and  $\mu_{rot}(H)$  is only involved in the transverse permeability.

The  $H$  dependence of  $\mu_{rot}$  can be known by calculating the transverse susceptibility  $\chi_{rot}$  from the rotational magnetization. Consider the rotation of a single domain with uniaxial anisotropy as a simple model [5], as shown the coordinate system in Fig. 1. The external field  $H$  and probe current  $I$  act along the ribbon axis. The easy axis makes an angle  $\theta_k$  from the transverse direction and  $H_t$  is transverse field produced by longitudinal probe current. The energy for magnetization  $M_s$  tilted away from easy axis by angle  $\theta$  is written as

$$E = K \sin^2\theta - M_s H_{ext} \sin(\theta + \theta_k) - M_s H_t \cos(\theta + \theta_k) \quad (3)$$

where  $K$  is the anisotropy constant.

The equilibrium angle can be determined by minimizing the energy, or by

\*Corresponding author

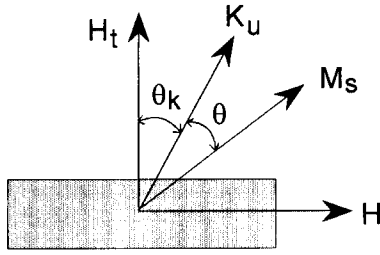


Fig. 1. Performance of feedback system to keep the interferometer signal constant (a) applied magnetic field, (b) interferometer signal and (c) feedback output.

$$\frac{\partial E}{\partial \theta} = K \sin(2\theta) - M_S H_{ext} \cos(\theta + \theta_k) + M_S H_t \sin(\theta + \theta_k) = 0 \quad (4)$$

The rotational transverse susceptibility can be obtain by the relation

$$\chi_{rot} = \frac{\partial^2 E}{\partial H_t^2} \quad (5)$$

After some partial derivative procedures with change of variables and taking small  $H_t$  field approximation, the Eq. (5) becomes

$$\chi_{rot} = \frac{M_s \sin^2(\theta + \theta_k)}{H_k \{h \sin^2(\theta + \theta_k) + \cos(2\theta)\}} \quad (6)$$

where we defined anisotropy field  $H_k = 2K/M_s$  and  $h = H/H_k$ . It is a same result that is obtained by the precession of magnetic moment in dc frequency limit [1].

We can obtain  $\chi_{rot}(h)$  numerically for a given  $\theta_k$  from Eq. (4) and (6) as shown in Fig. 2. For the small angles  $\theta_k$ , the susceptibilities exhibit peaks near  $h = \pm 1$ , or  $H = \pm H_k$ . As  $\theta_k$  increases, the value of  $h$  at the peak decreases and the peak eventually disappears for further increase of  $\theta_k$ , giving monotonically decreasing  $\chi_{rot}$  with  $h$ . In actual amorphous materials, there are inevitable residual stresses, leading to local variations in the anisotropy direction. In spite of the spatial distribution of  $\theta_k$ , MI will shows peaks near because the local anisotropy near  $H = \pm H_k$  transverse direction,  $\theta_k \approx$

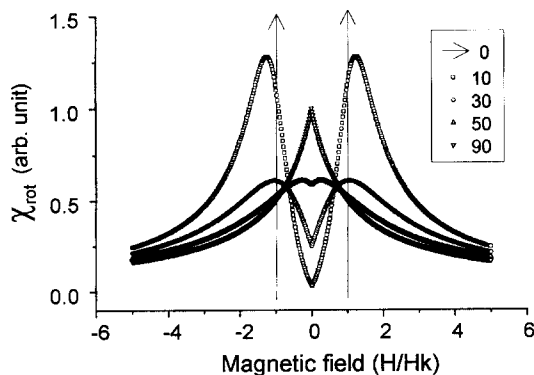


Fig. 2. Relative amplitude of the harmonics of magnetic induction for (a)  $\phi = 0^\circ$ , (b)  $40^\circ$  and (c)  $90^\circ$ .

$0^\circ$ , gives most pronounced peaks in  $\chi_{rot}$  as shown in Fig. 2.

### 3. Experimental

The Co-based amorphous ribbons ( $\text{Co}_{66}\text{Fe}_4\text{Ni}_1\text{B}_{14}\text{Si}_{15}$ ) have been annealed at various temperatures of 200-500 °C during 1 hour in  $10^{-3}$  Torr. The absolute value of impedance  $Z$  is measured by HP4192A impedance analyzer using four terminal contacts under the longitudinal magnetic field, which is produced by 0.01 Hz triangular current applied to a Helmholtz coil. The magneto-impedance ratio is obtained from the relation

$$\Delta Z / Z (\%) = \frac{[Z(H) - Z_{sat}] \times 100}{Z_{sat}} \quad (7)$$

where  $Z_{sat}$  is the impedance measured at  $H = 6$  Oe. MI ratio profile is obtained by measuring  $\Delta Z / Z$  during the cyclic applied field.

### 4. Results and Discussion

Figures 3(a)-(c) show the x-ray diffraction (XRD) using

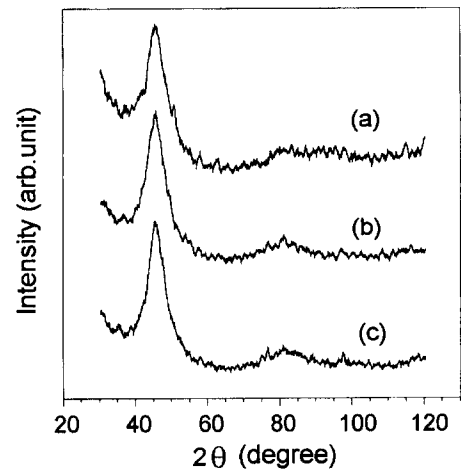


Fig. 3. x-ray diffraction in (a) as-quenched, (b) 400 and (c) 500 °C annealed samples.

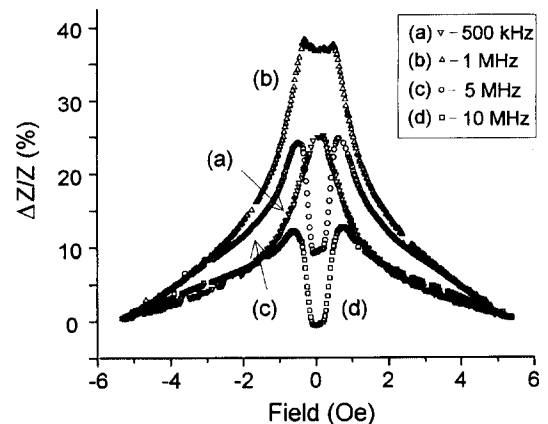


Fig. 4. MI profiles in as-quenched sample measured at various frequencies. (a) 500 kHz, (b) 1 (c) 5 (d) 10 MHz.

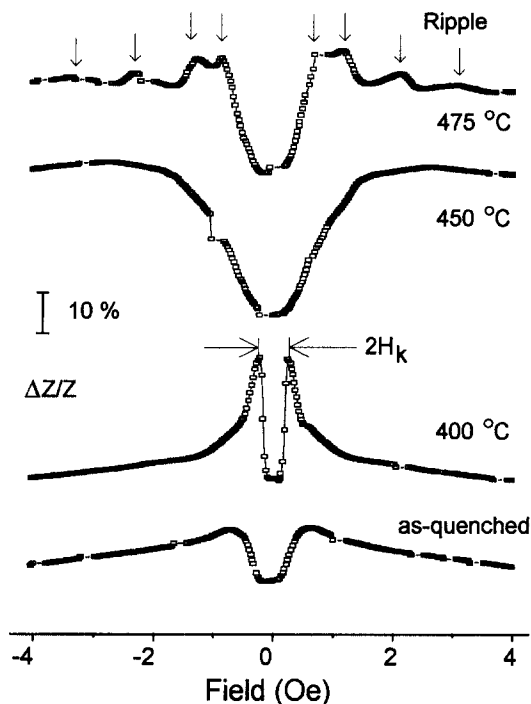


Fig. 5. MI profiles at  $f=10$  MHz in annealed samples.

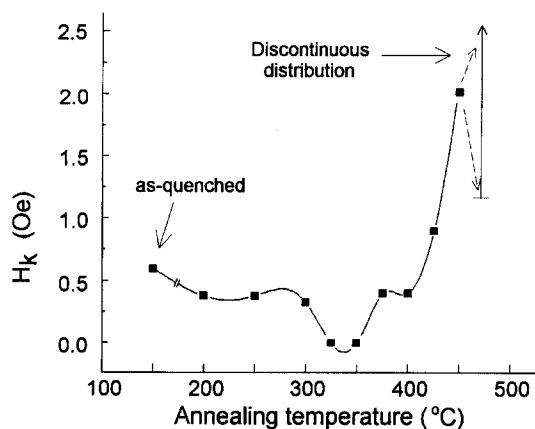


Fig. 6. Variation of the local anisotropy field with annealing temperature.

CuK $\alpha$  radiation in as-quenched, 400 and 500 °C annealed samples, respectively. There is no significant change in XRD patterns, indicating that most of sample volume is amorphous or nanocrystalline states after annealing up to 500 °C.

Figure 4 shows MI profiles at various frequencies of applied ac current in as-quenched sample. The monotonically decreasing MI with  $H$  at  $f=500$  kHz, that is, single peak profile, reflects that the domain wall motion is dominant mechanism in MI because  $\mu_{dw}(H)$  decreases with the field  $H$ . The MI ratio at high frequencies above 5 MHz increases initially with  $H$  to a peak and then fall with further increment. In this frequency range, the wall motion is nearly damped, then  $\mu_{rot}(H)$  is responsible for MI. Hence the value of  $H$  for MI peak corresponds to the local anisotropy field  $H_k$  of the rotated domains, as described in section 2.

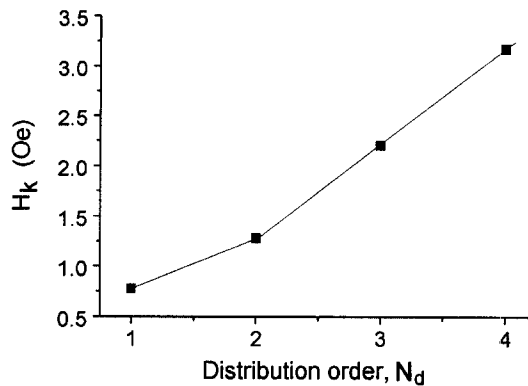


Fig. 7. Discontinuous distribution of anisotropy fields at 475 °C annealed sample.

Figure 5 shows the MI profile with annealing temperature  $T_a$  at  $f=10$  MHz, of which frequency the rotational magnetization only contributes to MI. MI profiles show sensitive variation with annealing temperatures, accompanied with the change of field interval between two peaks,  $2H_k$ . In addition, the field sensitivity of MI ratio for the range of  $H > H_k$  is higher for the sample of smaller  $H_k$ . For the samples of  $T_a=320, 350$  °C, MI profiles show single peak at  $H=0$ , indicating  $H_k$  is nearly equal to zero. It is worth to noticing that there are ripples (several peaks) in MI profile at  $T_a=470$  °C sample. For  $T_a=500$  °C sample, MI decreases drastically, and so it is hard to observe the distinct MI peaks.

The variation of  $H_k$  with  $T_a$ , determined from MI profile in Fig. 5, is shown in Fig. 6. As  $T_a$  increases up to 350 °C, the  $H_k$  of 0.6 Oe in as-quenched sample decreases to be less than 0.03 Oe due to the increase of magnetic softness in the nanocrystalline state by the annealing. However,  $H_k$  increases for the further increase of  $T_a$ , due to the onset of microcrystallization. There is ambiguity to determine  $H_k$  at  $T_a=475$  °C sample because of the several peaks in MI profile.

Several peaks at  $T_a=475$  °C sample could indicate the existence of discontinuous distribution of anisotropy fields, corresponding the peak's order to the distribution order,  $N_d$ . The anisotropy field varies linearly with the distribution order from  $N_d=2$ , as shown in Fig. 7. Such a discontinuous distribution of  $H_k$  may reflect that the microstructure in the initial crystallization state causes the different values of anisotropy field.

### 5. Conclusion

We have evaluated the variation of anisotropy field  $H_k$  in the annealed  $\text{Co}_{66}\text{Fe}_4\text{Ni}_{14}\text{B}_{14}\text{Si}_{15}$  amorphous by analyzing the measured MI profiles in terms of transverse permeability and domain dynamics. The decreasing  $H_k$  with the annealing temperature is ascribed for by the increase of magnetic softness, while the increasing  $H_k$  for the further increment of annealing temperature is associated with micro-

structural change by the annealing. The discontinuous distribution of  $H_k$  at 475 °C annealed sample may reflect that the microstructure in the initial crystallization state causes the different values of anisotropy field.

### Acknowledgement

The authors wish to acknowledge the financial support of the Korea Research Foundations made in the Program year 1997.

### References

- [1] L. V. Pannia, K. Mohri, T. Uchiyama, M. Noda, and K. Bushida, IEEE. Trans. Magn. **30**, 1249 (1995).
- [2] X. L. Yang, J. X. Yang, G. Chen, G. T. Shen, B. Y. Hu, and K. Y. Jiang, J. Magn. Magn. Mater. **175**, 285 (1997).
- [3] D. Atkinson and P. T. Squire, J. Appl. Phys., **83**, 6569 (1998).
- [4] S. S. Yoon, C. G. Kim, and H. C. Kim, J. Magn. Magn. Mater., accepted for publication, (1998).
- [5] D. Y. Kim, C. G. Kim, H. C. Kim, and U. H. Sung, J. Appl. Phys., **81**, 5811 (1997).