Sample Length Dependence of Giant Magnetoimpedance in Fe–Zr–Nb–Cu–B Nanocrystalline Ribbons

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In the present work the sample length dependence of giant magnetoimpedance for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons was investigated. With a reduction of sample length L , the peak field H_p of positive magnetoimpedance increases, due to an enhancement of demagnetization effect along the sample length direction. Meanwhile, a shortening of ribbon length brings about a decrease of the permeability change under field, which results in a drop of negative magnetoimpedance. In addition, the frequency $f_{\max}$ where the maximum of negative $(\Delta Z/Z_0)_{\max}$ occurs, shifts to higher frequencies with reduction of sample length. The giant magnetoimpedance in nanocrystalline ribbons depends not only on the field and frequency, but also sensitively on the sample length, which should be considered in designing of GMI electronic circuits.

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1. Introduction

The giant magnetoimpedance (GMI) effect consisting a change of impedance under dc magnetic fields in soft magnetic materials has attracted much attention due to its many technological applications such as field, current, or position sensors and magnetic heads.^{1–12} This effect has been observed in various families of soft magnetic materials, which is connected with the change of penetration depth via the permeability under fields. For practical applications, the miniaturization of sensors requires the smallest possible size of the GMI working elements. However, only small attention has been paid to the geometrical dimensions of sample,^{8,9} even though the shape anisotropy play an important role in determining macroscopic properties. In the present work, the sample length influence upon the giant magnetoimpedance in $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ annealed nanocrystalline ribbons has been investigated.

2. Experiments

The $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ alloy was prepared by arc — melting in Ar atmosphere. The metallic ribbons were obtained by the single roller melt— spinning technique with wheel speed of 40 m/s. The ribbon thickness is about 20 μm , and its width is 2 mm. Ribbons were cut into samples with lengths $L = 10, 30$ and 60 mm, and then annealed in vacuum for 20 min at a temperature of 725°C, respectively. The X-ray diffraction measurement of $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ annealed ribbon was performed with Cu $K\alpha$ radiation. The GMI measurements were carried out using an HP 4294A impedance analyzer at room temperature. The sample was connected to the analyzer with accessory test lead containing four cables, and placed in a Helmholtz coil which can produce DC fields up to 8 kA/m. The coils were so placed that the applied field was perpendicular to the earth's

magnetic field. The ac currents with the amplitude of 20 mA and dc fields were applied in the direction along the ribbon length for longitudinal magnetoimpedance measurement. The relative change of transverse real permeability under field was measured using a small coil with the equivalent impedance method by a HP 4294A impedance analyzer, where a dc field was applied perpendicular to the length of the sample as well as the coil.

3. Results and Discussion

Figure 1 shows the X-ray diffraction pattern of $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ ribbon annealed at 725°C for 20 min. The α -Fe phase occurs in the annealed ribbon. Based on Scherrer's equation, the average grain size of α -Fe was estimated as about 10 nm. Beside of the main phase of α -Fe, a very little of Fe_3Zr exists in the ribbon. Fe_3Zr -type phase was previously observed in nanocrystalline ribbons $\text{Fe}_{91}\text{Zr}_7\text{B}_2$ and $\text{Fe}_{86}\text{Zr}_7\text{B}_6\text{Cu}_1$ annealed at a high temperature such as 700°C.^{13,14}

Figure 2 shows the dc field dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons with different length $L = 10, 30$ and 60 mm. At frequencies $f = 0.3$ and 0.8 MHz,

Fig. 1 The X-ray diffraction pattern of $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ ribbon annealed at 725°C for 20 min.

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Fig. 2 The dc field dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons with different length $L = 10, 30$ and 60 mm.

there is a positive peak of magnetoimpedance at a smaller field H_p . Such peak was attributed to the existence of transverse anisotropy,¹⁰⁾ where the anisotropy field H_K equals to the peak field H_p . It is evident from Fig. 2 that the peak field H_p increases with the reduction of sample length L , which is related to the demagnetizing effect. The shorter the sample is, the larger the demagnetizing factor N along length direction becomes. A larger applied field H_{app} is needed to induce the impedance-peak for shorter sample. We also measured the frequency dependence of the H_p . The H_p increases with increasing frequency, which indicates there is a distribution of the anisotropy field H_k , along the direction perpendicular to the ribbon plane.^{4,7)}

The frequency dependence of the peak value of positive magnetoimpedance $(\Delta Z/Z_0)_p$ for different sample length $L = 10$ mm and 60 mm is presented in Fig. 3. With increasing frequency, the peak value of positive magnetoimpedance $(\Delta Z/Z_0)_p$ increases at first, experiences a maximum, and then drops again. The drop of $(\Delta Z/Z_0)_p$ can be attributed to the reduction of permeability with frequency.¹¹⁾ The positive maximum magnetoimpedance shifts to lower frequency with reduction of sample length.

Figure 4 shows the frequency dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ under different field $H = 796, 2387$ and 7162 A/m for samples $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ with different length $L = 10, 30$ and 60 mm. Large negative magnetoimpedance can be observed. The magnetoimpedance increases with increasing frequency at first due to the enhancement of skin effect, undergoes a maximum value at a certain frequency f_{max} , and finally drops again with further increase of frequency due to the decrease of permeability.¹¹⁾

Fig. 3 The frequency dependence of the peak value of positive magnetoimpedance for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons with different sample length $L = 10$ and 60 mm.

Fig. 4 The frequency dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ under different field $H = 796, 2387$ and 7162 A/m for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ with different length $L = 10, 30$ and 60 mm.

Fig. 5 The frequency dependence of the magnetoresistance $\Delta R/R_0$ and magnetoreactance $\Delta X/X_0$ under different field $H = 7162$ A/m for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ with different length $L = 10, 30$ and 60 mm.

The frequency dependence of magnetoresistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$ and magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$ under $H = 7162$ A/m are shown in Fig. 5. The drop of magnetoreactance results from the reduction of change of permeability with field. The frequency dependence of magnetoresistance and magnetoimpedance are similar, but their frequencies where maximum values occur are different. The magnetoimpedance is the combining effect of magnetoresistance and magnetoreactance. It can be seen from Fig. 4 that the longer the sample is, the larger the negative magnetoimpedance becomes, which is mainly due to the demagnetizing effect. The frequency $f_{\max}$ where the maximum of negative $\Delta Z/Z_0$ occurs, shifts to higher frequency with shortening the sample. Under $H = 7162$ A/m, values of $(\Delta Z/Z_0)_{\max}$ are -56.18% at $f_{\max} = 0.3$ MHz for $L = 60$ mm, -35.93% at $f_{\max} = 1$ MHz for $L = 30$ mm, and -20.46% at $f_{\max} = 2$ MHz for $L = 10$ mm. It was reported previously for an FeCrSiBCuNb wire that with decreasing wire length, the coercivity increases and initial susceptibility χ drops.⁸⁾ Similar to the wire, the demagnetizing field in ribbons may change the domain pattern at both ends of ribbon, reducing the magnetic properties of ribbon itself, especially for the very short sample. Meanwhile, the effective field H_{eff} upon the sample for the shorter sample is smaller than the longer one due to the demagnetizing field H_{dem} .

Figure 6 shows the frequency dependence of real permeability change $\Delta\mu'/\mu' = (\mu'(H) - \mu'(0))/\mu'(0)$ under $H = 7162$ A/m for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons with length $L = 10$ and 60 mm. The reduction of ribbon length brings about a drop of the permeability change, resulting in a smaller magnetoimpedance. Meanwhile, the permeability change $\Delta\mu'/\mu'$ is found to decrease with

Fig. 6 The frequency dependence of real permeability change $\Delta\mu'/\mu' = (\mu'(H) - \mu'(0))/\mu'(0)$ under $H = 7162$ A/m for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons with length $L = 10$ and 60 mm.

increasing frequency.

In conclusion, in the present work the sample length dependence of giant magnetoimpedance for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons was investigated. With the reduction of sample length L , the peak field H_p for positive magnetoimpedance increases, which is due to an increase of demagnetization effect. The reduction of ribbon length brings about a smaller permeability change, which results in a drop of negative magnetoimpedance. Meanwhile, the frequency $f_{\max}$ where the maximum of negative $(\Delta Z/Z_0)_{\max}$ occurs, shifts to higher frequencies with reduction of sample length. For example, under $H = 7162$ A/m, the value of $(\Delta Z/Z_0)_{\max}$ for $\text{Fe}_{84}\text{Zr}_{2.08}\text{Nb}_{1.92}\text{Cu}_1\text{B}_{11}$ nanocrystalline ribbons is -56.18% at $f_{\max} = 0.3$ MHz for $L = 60$ mm, and -20.46% at $f_{\max} = 2$ MHz for $L = 10$ mm.

REFERENCES

- 1) K. Mohri, T. Kohzawa, K. Kawashima, H. Y. Yoshida and L. V. Panina: IEEE Trans. Magn. **28** (1992) 3150–3152.
- 2) R. S. Beach and A. E. Berkowitz: Appl. Phys. Lett. **64** (1994) 3652–3654.
- 3) L. V. Panina and K. Mohri: Appl. Phys. Lett. **65** (1994) 1189–1191.
- 4) M. Vázquez, J. M. García-Beneytez, J. P. Sinnecker and L. Li: J. Appl. Phys. **83** (1998) 6578–6580.
- 5) J. Hu, L. Zhang, H. Qin, Y. Wang, Z. Wang and S. X. Zhou: J. Phys. D **33** (2000) L45–L47.
- 6) J. Hu, H. Qin, S. Zhou, Y. Wang and Z. Wang: Mater. Trans. JIM, **41** (2000) 1589–1592.
- 7) J. Hu, H. Qin, F. Zhang and R. K. Zheng: J. Appl. Phys. **91** (2002) 7418–7420.
- 8) M. Vázquez, Y.-F. Li and D.-X. Chen: J. Appl. Phys. **91** (2002) 6539–6544.
- 9) G. V. Kurlyanskaya, J. M. Barandiarán, M. Vázquez, D. García and N. V. Dmitrieva: J. Magn. Magn. Mater. **215–216** (2000) 740–742.
- 10) L. V. Panina, K. Mohri, T. Uchiyama and M. Noda: IEEE Trans. Magn. **31** (1995) 1249–1260.
- 11) J. Hu, H. Qin, L. Zhang and J. Chen: Mater. Sci. Eng. B **106** (2004) 202–206.
- 12) B. Li, J. Hu, H. Qin, N. Ma, K. An and X. Wang: J. Iron Steel Res. Int. **10** (2003) 55–57.
- 13) K. Suzuki, N. Kataoka, A. Inoue, A. Makino and T. Masumoto: Mater. Trans. JIM, **31** (1990) 743–746.
- 14) A. Makino, K. Suzuki, A. Inoue and T. Masumoto: Mater. Trans. JIM, **32** (1991) 551–556.