Investigation on the Giant Magnetoimpedance of Fe$_{89-x}$Zr$_7$B$_4$Al$_x$ ($x = 0$ and 2.5) Nanocrystalline Ribbons

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In the present work, annealing effects upon the crystallization and giant magnetoimpedance (GMI) of Fe$_{86.5}$Zr$_7$B$_4$Al$_{1.5}$ ribbons were investigated, in comparison with the case of Fe$_{89}$Zr$_7$B$_4$ ribbons. Annealing at 720°C for Fe$_{89}$Zr$_7$B$_4$ results in the formation of mixture of α-Fe and Fe$_2$Zr, and the appropriate addition of Al can restrain the Fe$_2$Zr precipitation. The optimum annealing temperature for obtaining the largest magnetoimpedance is 650°C for Fe$_{89}$Zr$_7$B$_4$, and is 720°C for Fe$_{86.5}$Zr$_7$B$_4$Al$_{1.5}$, where the permeability reaches its maximum value. The GMI effect depends not only on the permeability change with field, but also on the magnitude of the permeability itself. The reduction of the permeability ratio $\Delta Z/\Delta H_{\text{max}}$ under applied magnetic field $H = 7162$ A/m can reach $-43.3\%$ for Fe$_{89}$Zr$_7$B$_4$, and $-45.8\%$ for Fe$_{86.5}$Zr$_7$B$_4$Al$_{1.5}$. The appropriate Al addition in Fe-Zr-B ribbon not only lowers the transverse anisotropy, but also improves the change slope of impedance at low field ($H < 1000$ A/m).

1. Introduction

The giant magnetoimpedance (GMI) in soft magnetic materials has attracted much attention. Earlier works on GMI effect were on CoFeSiB amorphous wires.1-4 Now it has been extended to Co-Fe-Si-B amorphous ribbons,5-7 Fe-Zr-B,8,9 Fe-Zr-B-Cu,10,11 Fe-Zr-B-Cu-Al,12 Fe-Nb-B,13 Fe-Hf-B,14 Fe-P-C-Mo-Cu-Si,15 Fe-Cu-Nb-Si-B,16-18 Fe-Cu-Nb-Si-B-Al19 nanocrystalline ribbons, Ni-Fe-Mo permalloy wires/flakes,20,21 pure Fe wires,22,23 Ni-Fe/Cu/Ni-Fe,24 Co-Si-B/(Cu/Ag)/Co-Si-B25 sandwich films, Be-Cu/Ni-Fe,26 Ag/Ni-Fe,27 Cu/Cu-P28 plated wires, manganites La-A-Mn-O (A = Sr, Ba, Ca29,30) and Mn-Zn ferrites.31 The GMI effect consisting a sensitive change of impedance under a dc magnetic field is of important applications in various magnetic sensors. It was suggested that the GMI effect strongly depends on the variation of the penetration depth via permeability.2,7,30 There is an optimum annealing temperature for Fe based ribbons in order to obtain a large GMI.8-10,13-17 For Fe-Zr-B ribbons, annealing above 670°C for 20 min results in a weak GMI, accompanying the occurrence of Fe$_2$Zr phase.9 A higher annealing temperature above 650°C degrades soft magnetic properties in Fe-Zr-B due to the occurrence of Fe$_2$Zr and the coarsening of α-Fe grain.32 It was showed that an appropriate Al addition ($x = 2$) in Fe$_{73.5-x}$Cu$_x$Nb$_2$Si$_{13.5}$B$_7$Al$_6$ nanocrystalline ribbons increases the permeability and decreases the coercivity, due to the reduction of the magnetostructural anisotropy.33,34 A recent investigation on GMI of Fe$_{73.5-x}$Cu$_x$-Nb$_2$Si$_{13.5}$B$_7$Al$_6$ ($x = 0$ and 2) indicated that the Al addition ($x = 2$) improves GMI effect and its field sensitivity when compared to the Al-undoped nanocrystalline alloy.19 The GMI effect in Fe$_{82-x}$Zr$_7$B$_4$Cu$_x$Al$_y$ ($x = 2, 4, 6, 8$, $y = 0, 0.5, 1, 1.5$) nanocrystalline ribbons was already investigated at various annealing temperatures $T_A = 350, 450, 550$ °C, and results showed that small Al addition ($y \leq 1.5$) decreases GMI effects in Fe$_{82-x}$Zr$_7$B$_4$Cu$_x$Al$_y$ at low annealing temperature $T_A \leq 550$ °C.12 Since the optimum annealing temperature for the best magnetic softness32 and largest GMI10 in Fe-Zr-B is about 650°C, the investigation of GMI effect for Fe-Zr-B-Al in higher annealing temperatures above 550°C is needed. In the present work, the giant magnetoimpedance of Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ nanocrystalline ribbon was investigated in a wider annealing temperature range from 520 to 820°C, in comparison with the case of Al-undoped Fe$_{89}$Zr$_7$B$_4$.

2. Experiments

Fe$_{89-x}$Zr$_7$B$_4$Al$_x$ ($x = 0, 2.5$) ribbons with thickness of 20 μm were prepared by the melt-spinning technique. The wheel speed of Cu roller is 40 m/s. Ribbons were annealed in vacuum at different temperatures $T_A = 520, 550, 570, 620, 650, 670, 720, 760, 820$ °C for 20 min, respectively. The X-ray diffraction measurements of Fe$_{89-x}$Zr$_7$B$_4$Al$_x$ with $T_A = 550, 650, 670$ and 720°C were performed with Cu kα radiation. The ribbons with 2 mm width, 40 mm length were used in the longitudinal magnetoimpedance measurement. The amplitude of ac currents is 20 mA. 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 dc fields were applied perpendicular to the ribbon length. In order to evaluate the annealing temperature dependence of the permeability for nanocrystalline ribbons, the permeability ratio $\mu'(T_A)/\mu'(520°C)$, where $\mu'(T_A)$ and $\mu'(520°C)$ is the real-permeability at an annealing temperature $T_A$ and 520°C, was measured using ribbon-samples with a small coil at a frequency $f = 1$ kHz and a measuring field $H = 0.5$ A/m.
3. Results and Discussion

Figure 1 shows the X-ray diffraction patterns of Fe$_{86-x}$Zr$_x$B$_4$Al$_x$ ($x = 0$, 2.5) ribbons with annealing temperatures $T_A = 550$, 650, 670 and 720°C. Based on Scherrer’s equation, the average grain size of α-Fe precipitated from the amorphous matrix in the annealed ribbons Fe$_{86-x}$Zr$_x$B$_4$Al$_x$ can be estimated as 13–17 nm from the X-ray diffraction patterns. As shown in Fig. 1(a), annealing at $T_A = 720$°C for Fe$_{86}$Zr$_7$B$_4$ results in the formation of mixture of α-Fe and Fe$_3$Zr, however no evident diffraction peaks of Fe$_3$Zr phase can be observed in the ribbon Fe$_{86}$Zr$_7$B$_4$ annealed at $T_A = 670$°C. The Fe$_3$Zr phase was also observed in Fe$_{89}$Zr$_7$B$_4$ annealed at 700°C. It can be found from Fig. 1(b) that the peaks of Fe$_3$Zr in Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ ribbons annealed at $T_A = 720$°C is very weak and almost disappears. This indicated that the appropriate addition of Al can restrain the Fe$_3$Zr precipitation.

The annealing temperature $T_A$ dependence of the permeability ratio $\mu'(T_A)/\mu'(520°C)$ for Fe$_{86-x}$Zr$_x$B$_4$Al$_x$ ($x = 0, 2.5$) at $f = 1$ kHz and $H = 500$ A/m were shown in Fig. 2(a) and (b) respectively. With increasing annealing temperature, the real-permeability $\mu'$ increases at first, reaches a peak at $T_A = 650$°C for Fe$_{86}$Zr$_7$B$_4$ and $T_A = 720$°C for Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$, and finally drops again. For Fe$_{86}$Zr$_7$B$_4$, the $\mu'$ at $T_A = 720$°C is much smaller than that at $T_A = 650$°C, as shown in Fig. 2(a). The reduction of the permeability $\mu'$ at high annealing temperature $T_A$ is due to the occurrence of Fe$_3$Zr precipitation which has larger magnetocrystalline anisotropy and the coarsening of α-Fe grain. As shown in Fig. 2(b), the maximum permeability $\mu'$ for Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ appears at $T_A = 720$°C, which is interpretable as the suppression of Fe$_3$Zr precipitation by Al addition.

The dc field dependence of magneto-impedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ were plotted in Fig. 3(a) for Fe$_{89}$Zr$_7$B$_4$ at $T_A = 650$°C and in Fig. 3(b) for Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ at $T_A = 720$°C, respectively. At lower frequencies, the impedance increases monotonously with increasing field, due to the reduction of permeability, as shown in Fig. 4. At higher frequencies, the impedance undergoes a peak with an increase of dc field, which originates from the transverse anisotropy. The peak field (effective transverse anisotropy field) is 318 A/m at $f = 1$ MHz, 796 A/m at $f = 5$ MHz, 955 A/m at $f = 10$ MHz for Fe$_{89}$Zr$_7$B$_4$ at $T_A = 650$°C, and 159 A/m at $f = 1$ MHz, 318 A/m at $f = 5$ MHz, 477 A/m at $f = 10$ MHz for Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ at $T_A = 720$°C. This shows that addition of Al in Fe-Zr-B ribbon decreases the effective transverse anisotropy. Furthermore, compared Fig. 3(a) with Fig. 3(b), it can be seen that the impedance-change slope at low dc fields $H < 1000$ A/m is larger for Fe$_{86.5}$Zr$_7$B$_4$Al$_{2.5}$ at $T_A = 720$°C than for Fe$_{89}$Zr$_7$B$_4$ at $T_A = 650$°C. Correspondingly, compared Fig. 4(a) with Fig. 4(b) that the slope of...
permeability-change is larger for Fe$_{86.5}$Zr$_7$B$_4$:Al$_{2.5}$ than for Fe$_{89}$Zr$_7$B$_4$ under lower fields $H < 1000$ A/m.

Figure 5 shows the frequency dependence of the magnetoimpedance $\Delta Z/\bar{Z}_0$ for Fe$_{89}$Zr$_7$B$_4$ at $T_A = 650$°C, and for Fe$_{86.5}$Zr$_7$B$_4$:Al$_{2.5}$ at $T_A = 720$°C. There is a maximum magnetoimpedance $\Delta Z/\bar{Z}_0$ max of $\sim 43.3\%$ for Fe$_{89}$Zr$_7$B$_4$ at $f = 500$ kHz, and of $\sim 45.8\%$ for Fe$_{86.5}$Zr$_7$B$_4$:Al$_{2.5}$ at 700 kHz. It seems that the appropriate Al addition in Fe-Zr-B improves the GMI. The appearance of maximum magnetoimpedance $\Delta Z/\bar{Z}_0$ max is a result of the competition between a decrease of permeability change and an increase of skin effect with frequency.

The annealing temperature dependence of the maximum magnetoimpedance $(\Delta Z/\bar{Z}_0)_{\text{max}}$ under a dc field $H = 7162$ A/m were shown in Fig. 6(a) for Fe$_{89}$Zr$_7$B$_4$ and in Fig. 6(b) for Fe$_{86.5}$Zr$_7$B$_4$:Al$_{2.5}$, respectively. The optimum annealing temperature $T_A$ where the largest magnetoimpedance value occurs is 650°C for Fe$_{89}$Zr$_7$B$_4$, and is 720°C for Fe$_{86.5}$Zr$_7$B$_4$:Al$_{2.5}$. Compared with Fig. 6 with Fig. 2, it can be concluded that the largest magnetoimpedance occurs at a such annealing temperature $T_A$ where the permeability has a largest value. It shows that the GMI effect depends not only on the permeability change with field, but also on the magnitude of the permeability itself.

4. Conclusions

Annealing at 720°C for Fe$_{89}$Zr$_7$B$_4$ results in the formation of mixture of $\alpha$-Fe and Fe$_3$Zr, and the appropriate addition of
Fig. 6 The annealing temperature dependence of the maximum magnetoimpedance $(\Delta Z/Z_0)_{\text{max}}$ under a dc field $H = 7162 \text{ A/m}$ (a) for Fe$_{86}$ZrB$_4$; and (b) for Fe$_{86.5}$ZrB$_4$Al$_{1.5}$.

Al can restrain the Fe$_{9}$Zr precipitation. The optimum annealing temperature for GMI is 650°C for Fe$_{80}$Zr$_{7}$B$_{4}$, and is 720°C for Fe$_{86.5}$Zr$_{7}$B$_{4}$Al$_{1.5}$, where the permeability reaches its maximum value. The magnetoimpedance $(\Delta Z/Z_0)_{\text{max}}$ under $H = 7162 \text{ A/m}$ can reach $-43.3\%$ for Fe$_{80}$Zr$_{7}$B$_{4}$ and $-45.8\%$ for Fe$_{86.5}$Zr$_{7}$B$_{4}$Al$_{1.5}$. The addition of Al in Fe-Zr-B ribbon not only lowers the transverse anisotropy, but also improves the change slope of impedance at low fields, which may be useful in sensor-design.

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REFERENCES