Giant Magnetoimpedance in $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ As-Quenched Ribbons

Bo Li^{1,*}, Hongwei Qin², Juan Chen² and Jifan Hu²

¹Department of Functional Materials, Central Iron & Steel Research Institute, Beijing 100081, P. R. China

²Department of Physics, Shandong University, Jinan 250100, P. R. China

In this work, large values of magnetoimpedance from $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons is reported. With increasing Cu content, the magnetoimpedance first increases, undergoes a maximum value at $x = 3.5$, and then drops at higher Cu contents. The magnetoimpedance $\Delta Z/Z_0$ for the $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) as-quenched ribbon reaches -31.3% under a field of $H = 7162 \text{ A/m}$ at 1.2 MHz . The grain size of $\alpha\text{-Fe}(\text{Si})$ for as-quenched $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) ribbon is estimated as $14\text{--}16 \text{ nm}$. Results show that nanocrystalline Fe-Cu-(Nb,V)-Si-B ribbons with giant magnetoimpedance can be prepared directly from the melt-spinning technique without annealing. [doi:10.2320/matertrans.47.1728]

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1. Introduction

Giant magnetoimpedance (GMI) has attracted much attention, due to its important applications in magnetic sensors and heads.^{1–6} The main point of the GMI effect is the impedance variation with the change of permeability under a dc magnetic field via the penetration depth. This effect has been found in Co based amorphous and Fe based nanocrystalline materials. Previously, Fe-Cu-Nb-Si-B nanocrystalline ribbons, called FINEMET,⁷ used for GMI were prepared by annealing as-quenched amorphous.^{5,6} Recently it was shown that Fe-Cu-Nb-Si-B nanocrystalline ribbons with higher Cu atomic content and large GMI can be obtained directly from the melt-spinning technique without additional annealing processes.⁸ It has also been found previously that the melted alloy of Fe-Cu-Nb-Si-B has a large viscosity when the Nb content in the alloy is large, and the viscosity of the melted alloy can be lowered by partial replacement of high-cost Nb by less expensive V.⁹ In order to test the applicability of the melt-spinning technique in the preparation of other Fe based nanocrystalline ribbons and to explore new GMI materials, this work reports on the crystallization and GMI effect in $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons.

2. Experiments

The alloys $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 1, 1.5, 2, 2.5, 3, 3.5$ and 4) were obtained by arc-melting in an argon atmosphere. $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ribbons of approximately $20 \mu\text{m}$ thickness were prepared by the single roller melting-spinning technique with wheel speed of 35 m/s in an argon atmosphere. Compared with Fe-Cu-Nb-Si-B, the $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ribbons are easier to prepare, since viscosity of the Fe-Cu-(Nb,V)-Si-B melted alloy is lowered and flows move easily. As-quenched ribbons with 2 mm width, 25 mm length were used in the magnetoimpedance measurement with a HP 4294A impedance analyzer at room temperature. The sample was connected to the analyzer with the accessory test lead, and placed within Helmholtz

coils. The ac currents with an amplitude of 20 mA and dc fields were applied in the direction along the ribbon length for longitudinal magnetoimpedance measurement. The X-ray diffraction measurement of $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as quenched ribbons was performed with Cu $K\alpha$ radiation.

3. Results and Discussion

Figure 1 shows X-ray diffraction patterns for the as-quenched ribbons of $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$. The ribbon with $x = 1$ is mainly amorphous. Diffraction peaks of $\alpha\text{-Fe}(\text{Si})$ phase can be easily seen from Fig. 1 in the ribbons with higher Cu content ($x = 2$ to 4). The $\alpha\text{-Fe}(\text{Si})$ phase occurs in as-quenched ribbons without annealing. High Cu addition improves the nucleation of $\alpha\text{-Fe}(\text{Si})$ in $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as quenched ribbons, similar to the case of annealed Fe-Cu-Nb-Si-B.¹⁰ Among ribbons investigated in the present work, the ribbon with $x = 3.5$ has the strongest intensity for the (200) and (211) peaks of $\alpha\text{-Fe}(\text{Si})$. Based on Scherrer's equation,¹¹ the grain-size of $\alpha\text{-Fe}(\text{Si})$ for ribbon $x = 3.5$ was estimated as $14\text{--}16 \text{ nm}$. This shows that nanocrystalline ribbons of Fe-Cu-(Nb,V)-Si-B can be obtained directly from the melt-spinning technique.

Figure 2 shows the dc field dependences of magneto-resistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$, magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$, and magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for the $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbon. At lower frequencies ($f = 100 \text{ kHz--}1.2 \text{ MHz}$), the magnetoreactance $\Delta X/X_0$ changes monotonously due to the decrease of permeability with increasing field. At higher frequencies ($f = 2\text{--}10 \text{ MHz}$), a small peak occurs which originates from the transverse anisotropy in the ribbons.^{2,3} The position of the peak-field H_p , increases with frequency, showing the position dependence of anisotropy in the ribbons. In the $\Delta R/R_0$ vs. f curves, however, no peaks are observed from 100 kHz to 10 MHz , as displayed in Fig. 2. This shows that transverse anisotropy in $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) as-quenched ribbons are weak. Giant magnetoimpedance is observed in Fig. 2. The value of magnetoimpedance $\Delta Z/Z_0$ under $H = 7162 \text{ A/m}$ is -31.3% at $f = 1.2 \text{ MHz}$.

*Corresponding author, E-mail: lib@cisri.com.cn

Fig. 1 X-ray diffraction patterns for the as-quenched ribbons of $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$.

Figure 3 shows the frequency dependences of magneto-resistance $\Delta R/R_0$, magnetoreactance $\Delta X/X_0$, and magneto-impedance $\Delta Z/Z_0$ for $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons under $H = 7162 \text{ A/m}$. The magnetoreactance $\Delta X/X_0$ decreases with increasing frequency. As shown in Fig. 4, the permeability change $\Delta\mu'/\mu'(0) = (\mu'(H) - \mu'(0))/\mu'(0)$ under a transverse field of $H = 7162 \text{ A/m}$ reduces with increasing frequency. The reduction of $\Delta X/X_0$ with increasing frequency results from the decrease in the permeability-change $\Delta\mu'/\mu'(0)$. For low frequencies, there is an enhancement of magneto-resistance $\Delta R/R_0$ with frequency, which is due to the skin effect. The drop of $\Delta R/R_0$ at higher frequencies may be attributed to the huge reduction of the permeability. As the combined effect of resistance and reactance, $\Delta Z/Z_0$ increases at low frequencies, undergoes a maximum $(\Delta Z/Z_0)_{\max}$ at a certain frequency, and finally drops again. The maximum of $\Delta Z/Z_0$ is a result of the competition between the decrease of permeability-change and the increase of the skin effect.

The Cu content dependence of the maximum value $(\Delta Z/Z_0)_{\max}$ under $H = 7162 \text{ A/m}$ for as-quenched $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ribbons is shown in Fig. 5. The $(\Delta Z/Z_0)_{\max}$ for $x = 1$ is only about -9.4% . With increasing Cu content, the magnetoimpedance undergoes a maximum value of -31.3% at $x = 3.5$, and then drops again at higher Cu contents. As shown in Fig. 4, the relative changes of

Fig. 2 The dc field dependences of magneto-resistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$, magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$, and magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for the $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) as-quenched ribbon.

permeability under a transverse field of $H = 7162 \text{ A/m}$ for the ribbon with $x = 3.5$ are larger than those for the ribbon with $x = 1$. The large magnetoimpedance for the ribbon with $x = 3.5$ corresponds to the great change of transverse permeability.

4. Conclusions

In this work the giant magnetoimpedance of $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons was reported. With increasing Cu content, the magnetoimpedance first increases, and then drops after obtaining a maximum value at $x = 3.5$. We have obtained a value of -31.3% for the magnetoimpedance $\Delta Z/Z_0$ under a field of $H = 7162 \text{ A/m}$ at 1.2 MHz for the $\text{Fe}_{71}\text{Cu}_{3.5}\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) as quenched ribbon. The grain size of $\alpha\text{-Fe(Si)}$ for $\text{Fe}_{71}\text{Cu}_{3.5}$ -

Fig. 3 The frequency dependences of magnetoresistance $\Delta R/R_0$, magneto-reactance $\Delta X/X_0$, and magnetoimpedance $\Delta Z/Z_0$ for $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons under $H = 7162 \text{ A/m}$.

$\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ ($x = 3.5$) was estimated as 14–16 nm. Nanocrystalline ribbons of Fe-Cu-(Nb,V)-Si-B with giant magnetoimpedance can be obtained directly from the melt-spinning technique without annealing, making them easy to form and therefore an attractive alternative for application in magnetic sensors and heads.

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Fig. 4 The frequency dependences of the permeability change $\Delta\mu'/\mu'(0) = (\mu'(H) - \mu'(0))/\mu'(0)$ for $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons ($x = 1$ and 3.5) under a transverse field of $H = 7162 \text{ A/m}$.

Fig. 5 The Cu content dependence of the maximum value $(\Delta Z/Z_0)_{\max}$ under $H = 7162 \text{ A/m}$ for $\text{Fe}_{74.5-x}\text{Cu}_x\text{Nb}_{1.5}\text{V}_{1.5}\text{Si}_{13.5}\text{B}_9$ as-quenched ribbons.

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