Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Magnetism and Magnetic Materials 285 (2005) 55–59

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Giant magneto-impedance effect on nanocrystalline microwires with conductive layer deposit

R.L. Wang, Z.J. Zhao*, L.P. Liu, W.Z. Yuan, X.L. Yang

Department of Physics, Center of Functional Nanomaterials and Devices, East China Normal University, 3663 Zhongshan North Rd., Shanghai 200062, PR China

Received 19 February 2004; received in revised form 15 July 2004
Available online 3 August 2004

Abstract

In this study, the giant magneto-impedance effect on Fe-based glass-coated nanocrystalline microwires with and without an additional outer copper layer was investigated. Experiment results showed that the magneto-impedance ratio of the wires with a layer of deposited copper is higher at low frequencies and lower at high frequencies (above 50 MHz), as compared to that of the microwires without an outer copper layer. The peak MI magnetic field, corresponding to the maximum of the magneto-impedance ratio shifts towards higher field values with increasing coating thickness of copper layer. The results are explained in terms of electro-magnetic interactions between the conductive layer and the ferromagnetic core.

PACS: 75.50.Tt; 75.47.−m

Keywords: Nanocrystalline; Giant magneto-impedance; Eddy current; Glass-coated

The giant magneto-impedance (GMI) effect was first observed in Co-based amorphous wires by Mohri et al. in 1992 [1]. It has since attracted much interest due to its potential applications in highly sensitive magnetic sensors and magnetic heads for recording. Much work has been carried out on the GMI effect in slightly negative magnetostrictive Co-base amorphous wires, films and ribbons. Recently, Fe-based nanocrystalline materials are fast gaining immense popularity as a new family of GMI materials due to its low constants of the crystalline magnetic anisotropy and magnetostriction λ_s [2]. Recent investigations show that a large change of impedance can occur at much lower frequencies in the multilayer structure, consisting essentially of two soft ferromagnetic layers sandwiching a non-magnetic highly conductive layer [3]. In addition, the frequency corresponding to

---

*Corresponding author. Tel.: +86-21-6223-2763; fax: +86-21-5251-0090.

E-mail address: zjzhao@phy.ecnu.edu.cn (Z.J. Zhao).

0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2004.07.014

the maximum magneto-impedance ratio also shifts towards lower value in such heterogeneous specimens such as composite wires with ferromagnetic core layer [4] or with a conductive core layer [5,6]. Thus, some authors considered the skin effect to be non-essential since the impedance can be changed considerably at relatively low frequencies [7]. However, the GMI effect was observed at lower frequencies in sandwiched films and composite wires, which is related not only to the intrinsic properties of the material but also to its geometric dimension. Therefore, the electromagnetic interactions between conductive layer and ferromagnetic layers must be considered.

In this work, the GMI effect on Fe-based nanocrystalline microwires, with a copper outer core, was investigated. The outer copper core was deposited by means of electroless deposition. Experimental results show that the GMI effect is obviously and closely related to both the driving frequency and the coating thickness of the copper layer. The maximum MI ratio of such composite wires was observed to increase at low frequencies and decrease at high frequencies. Furthermore, the peak magnetic field corresponding to the peak in MI ratio varies with the copper layer thickness. Results indicate that the principal mechanism explaining the GMI effect is primarily the electromagnetic interactions via inductive effect between the conductive layer and the ferromagnetic core. This is caused by the factors associated with the presence of the AC driving current, namely the variation of eddy current and skin depth.

The amorphous microwires of nominal compositions $Fe_{73.0}Cu_{1.0}Nb_{1.5}V_{2.0}Si_{13.5}B_{9.0}$ were prepared by glass-coated melt-spinning method. Each microwire consists of a metallic nucleus of diameter 5 μm and a glass coating thickness of 1 μm. All of the wires with 30 mm in length were annealed at 570 °C for 30 min in nitrogen atmosphere to obtain soft nanocrystalline materials. To deposit a layer of copper onto the microwires, electroless deposition was carried out. Then, the glass-coated microwires were carefully cleaned with distilled water and their surface was activated by Pb/Sn particles before being mounted and placed into the electroless-deposition bath. Operating temperature was controlled at 293 K using a water bath and pH value is maintained at 13.1 (controlled by adding sodium hydroxide). The bath composition and operating conditions are also listed in Table 1. The copper thicknesses ranged from 1 μm to 2 μm were obtained by controlling the deposition time. The GMI effect was measured using an HP4294A impedance analyzer. The constant alternating current $I_{\mathrm{rms}} = 5\,\mathrm{mA}$ flows through the metallic nucleus and the frequency f range from 100 kHz to 110 MHz. The magneto-impedance (MI) ratio has been defined as

$$\frac{\Delta Z}{Z}\% = \frac{Z(H_{\mathrm{ex}}) - Z(H_{\mathrm{max}})}{Z(H_{\mathrm{max}})} \times 100\%, \tag{1}$$

where $Z(H_{\mathrm{ex}})$ and $Z(H_{\mathrm{max}})$ are the impedance values of a sample in a magnetic field and in the maximum magnetic field H_{max}, respectively. The DC external magnetic field was generated by a pair of Helmholtz coils.

Table 1
Bath composition and operating conditions for electroless Cu

Components	Concentration
$CuSO_45H_2O$	10 g/l
$KNaC_4H_4O_6\ 4H_2O$	22 g/l
$NaBH_4$	1.3 g/l
$NH_4\ H_2O$(25%)	140 ml/l
NaOH	10 g/l
pH (with NaOH)	13.1
Temperature	293 K

Fig. 1 illustrates the MI effect curves tested at different frequencies for as-drawn glass-coated amorphous wires. It can be seen that the maximum MI ratio is 19% at 70 MHz. Fig. 2 shows the MI effect curves for the microwire annealed at 570 °C. The maximum MI ratio is found to be 114% at 70 MHz. The sample annealed at 570 °C shows much larger MI ratio than the as-drawn microwires [8]. The nanocrystalline microwire possesses excellent soft magnetic properties, due to the reduction of effective anisotropy as explained by random anisotropy model [9].

Fig. 3 shows the MI ratio tested at different frequencies for Fe-based nanocrystalline glass-coated microwires with copper layer of 1.5 μm in thickness. It can be seen that it exhibit the same trend against the external magnetic field as the