Giant Magnetoimpedance in Ti/CoP Plated Wires

Jifan Hu*, Hongwei Qin, Ling Zhang, Zhuo Wang and Minhua Jiang

Department of Physics and State Key Laboratory for Crystal Materials, Shandong University, Jinan 250100, P.R. China

The giant magnetoimpedance in Ti/CoP plated wires with various CoP thickness was investigated. There is an optimal thickness of CoP magnetic layer for obtaining a large magnetoimpedance. The frequency $f_{x}$ where the maximum magnetoimpedance $(\Delta Z/Z_0)_{\text{max}}$ occurs, shifts to low frequency with an increase of CoP thickness. Such shift is correlated with the reduction of the effective critical frequency of skin effect, accompanying the increase of magnetic layer thickness. The magnetic anisotropy field $H_K$ for Ti/CoP composite wires depends not only on the radial distance of CoP from the axis of the wire, but also on the CoP thickness.

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1. Introduction

In recent years the giant magnetoimpedance (GMI) effect in soft magnetic materials has attracted great attention because of its important application in micromagnetic sensors. The GMI effect consists in a magnetic field induced changes in the complex impedance due to the variation of magnetic permeability. Besides of the uniform wires, ribbons and films, this effect has been observed in inhomogeneous structured materials such as non – magnetic conducting wire plated with magnetic layers and some sandwich films. Large GMI effect occurs at a relative low frequency in BeCu/NiFe, BeCu/CoFeNi, Ag/NiFe and Cu/CoP plated wires. Most of previous published papers treated magnetoimpedance on plated wires with a constant magnetic thickness. Up to now no detailed experimental data about the influence of magnetic layer thickness on the GMI effect were given yet, except one report on Cu/CoP wires with CoP thickness $D$ of 3, 4 and 7 μm. The magnetoimpedance was found to enhance with increase of $D$ from 3 to 7 μm, and the $(Z(H) - Z(H_{\text{max}}))/Z(H_{\text{max}})$ (here $H_{\text{max}} = 377 \times 10^{3} / \mu A / m = 30 kA / m$) reached 200% at measuring current amplitude $I = 1 m A$ for a CoP/Cu composite wire with $\phi = 190 \mu m$, $D = 7 \mu m$, where $\phi$ is the Cu diameter. It was suggested that the amplitude of the GMI effect is raised considerably when the conductivity of the inner-core is much larger than that of the outer-layer region. The room temperature permeability of Ti ($\sigma = 2.26 \times 10^{6} \Omega^{-1} m^{-1}$) is smaller than that of Cu ($\sigma = 5.81 \times 10^{7} \Omega^{-1} m^{-1}$). Choosing Ti as the inner core is helpful to understand the influence extent of the inner core conductivity upon the GMI effect in plated wires. In the present work, the GMI effect in Ti/CoP plated wires with various thickness (5~125 μm) of magnetic layer CoP was investigated.

2. Experiments

A Co$_{80}$P$_{12}$ layer with various thickness of 5, 20, 30, 60, 70, 85 and 125 μm was electroplated onto Ti wires with diameter $\phi$ of about 190 μm, respectively. In electrodeposition process, the electrolyte was prepared by CoSO$_4$·7H$_2$O, Na$_3$HP·H$_2$O, H$_3$BO$_3$, KCl and citric acid. The pH value of plating bath was adjusted as 5. The current density in plating was 300 A/m$^2$. The thickness of CoP layer was derived by measuring the difference between the plated composite wires and pure Ti wires using a micrometer, and by observing a cross section of plated wires using a microscope. The Ti/CoP plated wires with $6 \times 10^{-2}$ m length were used in the magnetoimpedance (MI) measurements with a HP4294A impedance analyzer at room temperature. The plated wire was connected to the analyzer with a test lead containing four cables, and set within Helmholtz coils, which produce a dc magnetic field $H < 7957$ A/m. The coils were placed in such a way that the applied field was perpendicular to the earth’s magnetic field. The ac currents (with the amplitude of 20 mA) and dc magnetic fields were applied parallel in the direction along the plated wires.

3. Results and Discussion

The dc field dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for the Ti/CoP plated wire with a CoP thickness $D = 70 \mu m$ was shown in Fig. 1. At a low frequency $f = 100$ kHz, the magnetoimpedance changes monotonically with field, which may be due to the decrease of permeability. At high frequencies such as $f = 900$ kHz, $2$ MHz and $10$ MHz, with increase of the field the magnetoimpedance increases at first, undergoes a positive peak at a certain field $H = H_p$, and then drops again. Such peak also occurs in the field dependence of magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$ and magnetoresistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$, as plotted in Fig. 1. Similar peak phenomenon was observed in the uniform wires, ribbons and films, which was attributed to the existence of circumferential or transverse anisotropy and the permeability peak around anisotropy field $H_K$ ($H_K \approx H_p$). It has been found that in the electrodeposited CoP film there is a transition of magnetic anisotropy with regards to the thickness $D$ of CoP: For $D < 0.4 \mu m$, the anisotropy is planar. For $0.4 \mu m < D < 10 \mu m$ it is an oblique anisotropy. For larger thickness $D > 10 \mu m$, a perpendicular anisotropy occurs. By analogy, a development of magnetic anisotropy around certain CoP thickness is likely to appear for the Ti/CoP plated wires.
For the Ti/CoP composite wire with CoP layer $D = 70 \mu m$, the perpendicular or radial anisotropy may occur. The impedance peak phenomenon in this wire may be correlated with the existence of magnetic anisotropy $H_K$. This provides a new way to study the anisotropy of plated wires in return. In addition, it can be seen from Fig. 1 that at frequencies 900 kHz and 2 MHz, the magnetoimpedance does not reach its saturation value at $H = 90 \times 10^3 / 4\pi A/m$ (about 7162 A/m). This GMI response up to high fields in Ti/CoP plated wires is very promising for its application in magnetic sensors.

Similar to the uniform GMI material, the peak field $H_P$ in Ti/CoP plated wires ($D = 60$ and 125 $\mu m$) increases with an increase of ac current frequency, as shown in Fig. 2. As we know, with increasing ac frequency, an ac current tends to flow through a layer closer to the surface of the wire due to skin effect. It seems that the $H_K$ depends on the radial distance from the axis of the wire, being the function of the position.20,21) It should be noted that besides of the $H_K$ originated from the preparation processes, the magnetic field resulting from the eddy currents may make its contribution to the impedance – peak phenomenon.22) Furthermore, it can be seen from Fig. 2 that the $H_P$ for the sample with $D = 125 \mu m$ are larger than those with $D = 60 \mu m$. This shows that the $H_K$ for composite wire Ti/CoP enhances with an increase of $D$.

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The ac frequency dependence of magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$, magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$ and magnetoresistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$ for the Ti/CoP plated wire with a CoP thickness $D = 70 \mu m$.

Fig. 1 The dc field dependence of the magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$, magnetoreactance $\Delta X/X_0 = (X(H) - X(0))/X(0)$ and magnetoresistance $\Delta R/R_0 = (R(H) - R(0))/R(0)$ for the Ti/CoP plated wire with a CoP thickness $D = 70 \mu m$.

Fig. 2 The frequency dependence of the peak-field $H_P$ for Ti/CoP plated wires with CoP thickness $D = 60$ and 125 $\mu m$. A similar GMI response up to high fields in Ti/CoP plated wires is very promising for its application in magnetic sensors.

The CoP thickness dependence of the $\Delta Z/Z_0$ at $H = 7162 A/m$ and its corresponding $f_z$ for the Ti/CoP plated wires were shown in Fig. 4. The value of $\Delta Z/Z_0$ at $H = 7162 A/m$ for Ti/CoP wire ($D = 5 \mu m$) is only $-3.66\%$, smaller than those of Cu/CoP wires ($D = 4, 7 \mu m$), which is due to the smaller conductivity of Ti ($\sigma = 2.26 \times 10^4 \Omega^{-1} m^{-1}$) than that of Cu ($\sigma = 5.81 \times 10^5 \Omega^{-1} m^{-1}$). It confirmed the previous suggestion that large conductivity difference between magnetic layer and nonmagnetic core – metal in plated wires favors the GMI effect.17,18) For plated wires Ti/CoP with thin CoP
layer, the \((\Delta Z/Z_0)_\text{max}\) increases with increasing CoP thickness. Similar experimental results was observed in Cu/CoP plated wires \((D = 4-7 \mu m)\). What is the saturation for the thick CoP layer? We investigated this problem experimentally. We found there is an optimal \(D\) of CoP magnetic layer for obtaining a large \((\Delta Z/Z_0)_\text{max}\) in Ti/CoP plated wires. An previous theoretical calculation has already predicted that there is an optimal nonmagnetic inner layer for GMI effect in sandwich films.\(^{18}\) Thus, we think that the existence of optimal thickness for GMI may be a general thing for plated wires and sandwich films, even though its mechanism is not clear for us at present time.

It can be seen from Fig. 4 that the \((\Delta Z/Z_0)_\text{max}\) at \(H = 7162 \text{ A/m}\) is about 30\% for \(D = 60 \mu m\), which is smaller than the corresponding value \(-38\%\) of nanocrystalline FeCuNbSiB annealed ribbons.\(^{23}\) However, Ti/CoP plated wires is much easier to be produced industrially and has a better reproducibility than nanocrystalline Fe based and amorphous Co based materials, which is very important for application. As presented in Fig. 4, the \(f_Z\) shifts to low frequency with an increase of \(D\). For example, \(f_Z\) is 2 MHz at \(D = 20 \mu m\) and 700 kHz at \(D = 125 \mu m\). Such shift is correlated with the reduction of the effective critical frequency of skin effect, accompanying the increase of magnetic layer thickness.\(^{11}\) For Ti/CoP plated wires with small CoP thickness such as \(D = 20-85 \mu m\) it can be seen from Fig. 3 that there is an increase of magnetoreactance with increasing frequency at low frequency ranges. This phenomenon tends to disappear when the \(D\) become larger, as shown in the case \(D = 125 \mu m\). In addition, the peak of the magnetoresistance with respect to the ac frequency is very

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**Fig. 3** The ac frequency dependence of magnetoimpedance \((Z(H) - Z(0))/Z(0)\), magnetoreactance \((X(H) - X(0))/X(0)\) and magnetoresistance \((R(H) - R(0))/R(0)\) under \(H = 7162 \text{ A/m}\) for Ti/CoP plated wires with different thickness \(D\) of CoP layers.

**Fig. 4** The CoP thickness dependence of the maximum magnetoimpedance \((\Delta Z/Z_0)_\text{max}\) and its corresponding frequency \(f_Z\) for the Ti/CoP plated wires.
sharp for the sample with $D = 20 - 30 \mu m$. Figure 5 shows the CoP thickness dependence of the $(\Delta R/R_0)_{\text{max}}$ and its corresponding $f_R$ for the Ti/CoP plated wires. Similar to the case of magnetoimpedance, with increasing magnetic layer thickness the $(\Delta R/R_0)_{\text{max}}$ also undergoes a peak, and the corresponding peak frequency $f_R$ decreases monotonically.

4. Conclusions

In the present paper, the giant magnetoimpedance in Ti/CoP plated wires with various CoP thickness was investigated. The magnetic anisotropy field $H_K$ for composite wire Ti/CoP depends not only on the radial distance of CoP from the axis of the wire, but also on the CoP thickness. The $H_K$ enhances with an increase of thickness of magnetic layer CoP. There is an optimal thickness of CoP magnetic layer for obtaining a large magnetoimpedance. The frequency $f_Z$ where the maximum magnetoresistance $(\Delta Z/Z_0)_{\text{max}}$ occurs, shifts to low frequency with an increase of CoP thickness $D$. The magnetoimpedance $(\Delta Z/Z_0)_{\text{max}}$ at $H = 7162$ A/m is about 30% for $D = 60 \mu m$, which is slightly smaller than those of nanocrystalline Fe based materials and amorphous Co based materials. However, Ti/CoP plated wires have some advantages over them. Ti/CoP plated wires is much easier to be produced industrially and has a better reproducibility than nanocrystalline Fe based materials and amorphous Co based materials. The another important advantage of Ti/CoP plated wires is its good GMI response up to high fields, which is very promising for application in sensing devices.

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