Giant Magneto-impedance Effect in Composite Wires with Different Core Layer

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Abstract: Composite structure materials were potential sensing elements for magnetic sensors due to Giant magnetoimpedance (GMI) effect. Two kinds of composite wires with different magnetic/non-magnetic structures were fabricated by using electroless deposition methods and the magnetoimpedance properties were investigated. The maximum GMI ratio of 114% was acquired at 60 MHz in the composite wires with a ferromagnetic core, whereas, 116% of maximum GMI ratio was found in the composite wires with a conductive core at low frequency of 600 kHz. These results exhibit that the GMI ratio reaches the maximum when magnetoresistance ratio $\Delta R/R$ and magnetoinductance ratio $\Delta X/X$ make the comparative contributions to the total magnetoimpedance (MI). The obvious GMI effect obtained in the composite wires with conductive core frequency may provide a candidate for applications in magnetic sensors, especially at low frequencies.

Keywords: Composite wires; Electroless deposition; Giant Magnetoimpedance effect; Resistivity

Introduction

The giant magnetoimpedance (GMI) effect was firstly observed in Co-based amorphous wires by Mohri *et al* in 1992 [1]. It has attracted much interest due to its stability and small size for potential applications in highly sensitive magnetic sensors. Many researchers have investigated GMI effect in different soft magnetic materials including homogeneous and composite materials [2-6]. It was found that GMI origins from classical electrodynamics, which relates to inductive effect, skin effect and ferromagnetic resonance. GMI effect is a preferable way to verify domain structure and saturation magnetostriction coefficient of magnetic materials as a research tool [7]. Simultaneously magnetometer based on GMI effect was developed in practical applications [8].

GMI effect can be improved by using suitable amorphous or nanocrystalline soft magnetic materials with special geometric structures (microwire, ribbon and thin film) under optimized heat-treatment conditions [9-15]. For composite structures, such as composite wires and sandwiched films, their GMI ratios are much larger than those of homogeneous samples with the same dimensions and of similar ferromagnetic materials. The possible mechanism is enhancement of the skin effect due to electromagnetic interactions. If an insulator layer is added between two layers, composite wires with ferromagnetic core (CWFC) and composite wires with conductive core (CWCC) can be produced [16,17]. The GMI effect may be further enhanced if the thickness of the insulator is suitable for CWCC. The influence of conductive layer for CWFC is not too much. The mechanism is still unclear until now.

Among a variety of techniques for preparation of composite wires, such as electrodeposition [10] and

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magnetic sputtering [12,13], electroless deposition was believed to be the most suitable method due to its ability to provide uniform surface and cost-effectiveness of the fabrication process [14]. In this work, CWFC and CWCC are prepared using an electroless deposition method. Their GMI properties were comparatively studied.

Experimental

The detailed fabrication processes of two kinds of composition wires were reported in our previous work [16]. Firstly, the amorphous microwires of $Fe_{73.0}Cu_{1.0}Nb_{1.5}V_{2.0}Si_{13.5}B_{9.0}$ were prepared by a glass-coated melt-spinning method [19]. Then, the microwires were annealed at 570℃ for 30 min in nitrogen atmosphere to improve their soft magnetic properties. Finally, a layer of copper was deposited onto the microwires by using an electroless deposition method, and the composite wires with ferromagnetic core were obtained.

The composite wire with conductive core, that is, with Cu/insulator/NiCoP structure, was also produced by using an electroless deposition. The Cu wires 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. The bath composition contains $NiSO_4 \cdot 6H_2O$, $CoSO_4 \cdot 7H_2O$, $Na_2C_4H_4O_6 \cdot 2H_2O$ and $Na_3C_6H_5O_7 \cdot 2H_2O$. Operating temperature was controlled at 363 K using a water bath and pH value is maintained at ∼11. The deposition products were annealed at 200℃ to improve their soft magnetic properties.

The surface and the thickness of the plated layer of the samples were observed on scanning electron microscope (SEM, JSM-5610LV). The GMI effect was measured on an impedance analyzer (HP4294A). The constant alternating current I_{rms}=5 mA flows through the metallic nucleus and the frequency f ranges from 40 Hz to110 MHz. The ratio was defined as,

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

$$\frac{\Delta R}{R}(\%) = 100 \times \frac{R(H_{ex}) - R(H_{max})}{R(H_{max})}(\%) \quad (2)$$

$$\frac{\Delta X}{X}(\%) = 100 \times \frac{X(H_{ex}) - X(H_{max})}{X(H_{max})}\% \quad (3)$$

where Z, R, X are impedance, the real and imaginary component of the impedance, respectively. H_{ex} and H_{max} are an arbitrary and maximum intensity of external magnetic field, respectively. The DC external magnetic field was generated by a pair of Helmholtz coils.

Results and discussion

Figure 1 shows a typical SEM view of the two kinds of composite wires. It can be seen that the wires are composed of different layers and the plated surface is smooth. For CWFC wires as shown in Fig. 1(a), the diameter of ferromagnetic core is 7.0 μm. The thickness of coated glass layer and outer conductive layer is respectively 1.0 μm. For CWCC wires as shown in Fig. 1(b), the diameter of copper core is 90 μm. The thickness of coated Polyester ethylene is 5.0 μm and outer ferromagnetic layer is 7.0 μm. Figure 1(c) and 1(d) show the cross-section schematic diagrams of two kinds of wires.
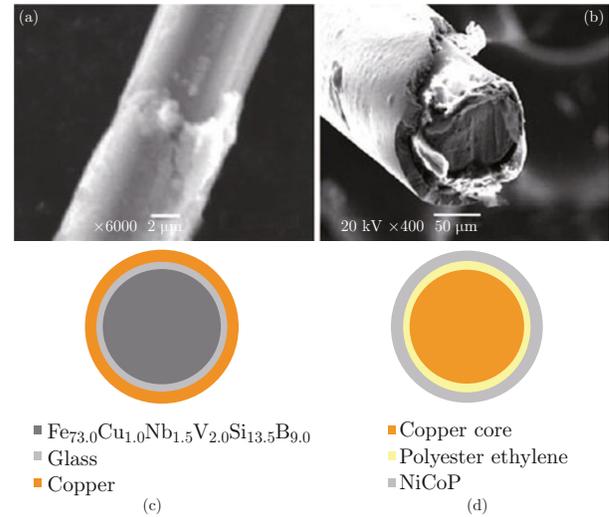
Fig. 1   SEM images and sectional view of two kinds of composite wires. (a) and (c) for CWFC; (b) and (d) for CWCC.

The MI effect curves for glass-coated microwires annealed at 570℃ tested at different frequencies are shown in Fig. 2. It can be seen that the maximum MI ratio is 118% at 60 MHz. Amonotonic decrease of the MI effect curve was observed at low testing frequency. However, at high testing frequency, the MI ratio increases initially with H_{ex} till it reaches a peak and then falls with further increase of the external field. The MI effect is closely relative to the change in circumferential permeability of the wire with respect to the external field. At low frequencies, the domain wall displacement dominates to the magnetization process [18]. The circumferential permeability decreases with increasing external magnetic field. Along with the increasing of the driving frequency, the domain wall displacement is nearly damped and moment rotation will dominate the magnetization process.

Comparing to the microwires, the MI curves of the CWFC display the similar trend, as shown in Fig. 3. The maximum MI ratio is found to be 114% at 60 MHz.
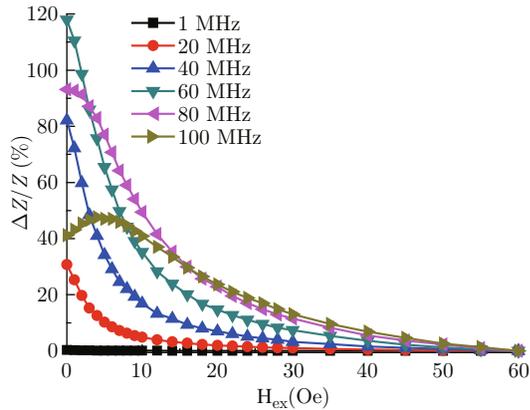
Fig. 2   MI ratio in variation with an external magnetic field for the microwires.
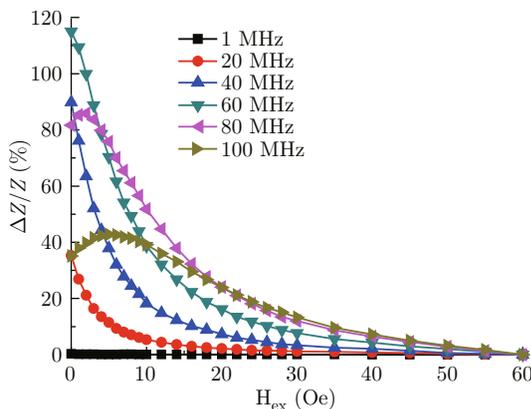
Fig. 3   MI ratio in variation with an external magnetic field for the CWFC.
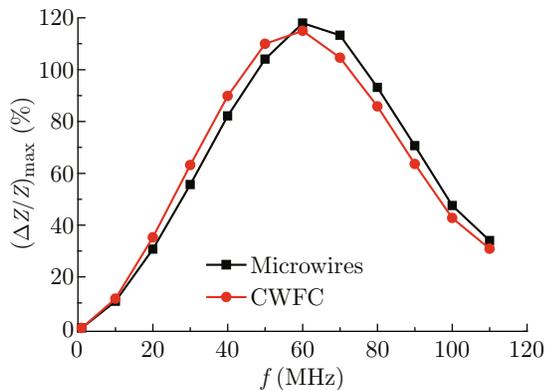
Fig. 4   The maximum GMI ratio with frequency for the CWFC and the microwires.

The dependence of the maximum MI ratio on the driving frequency for the CWFC and the microwires is given in Fig. 4. It can be seen that the GMI magnitude of the CWFC is different from that of the microwires. The MI ratio of the CWFC is higher than that of the microwires when the testing frequency is less than 60 MHz. However, the results are just the opposite when the testing frequency is more than 60 MHz. The circumferential

permeability changes due to the electromagnetic interaction between the copper layer and ferromagnetic core [16].

The above mentioned results show that the eddy current in the copper layer is induced by the electromagnetic interactions, though AC current flows only through the ferromagnetic core. The magnetic field induced by the eddy current will in turn magnetize the ferromagnetic core, which will strengthen the dynamic magnetization at low frequencies. With the increase of the driving frequency, the influence of eddy current becomes more obvious. When the frequency is up to 60 MHz, the circumferential permeability is greatly reduced by eddy current loss. Thus the MI ratio decreases. However, the effect of copper layer is not remarkable in such kind of composite wires.

The external field dependence of MI ratio for the CWCC is illustrated in Fig. 5. It can be seen that the samples exhibit a peak MI ratio in variation with the external magnetic field, even at low testing frequencies. The MI ratio increases initially till it reaches a peak and then falls with further increase of the field. As it's mentioned above, the MI effect is relative to the changes in circumferential permeability with respect to the external field. The circumferential magnetization mainly proceeds via moment rotation for such kind of composite wire even at low frequencies. A maximum MI ratio of 116% was obtained at 600 kHz. The CWCC indicates obvious MI effect at low frequencies.
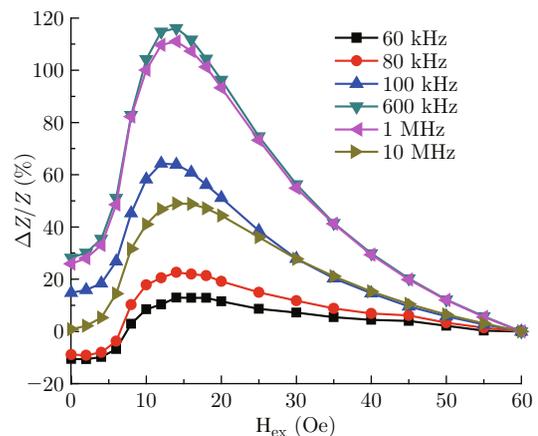
Fig. 5   MI ratio in variation with an external magnetic field for the CWCC.

To study the different influence of electromagnetic interaction on the two kinds of composite wires, the frequency dependences of $\Delta Z/Z$, $\Delta R/R$, $\Delta X/X$ of CWFC and CWCC have been depicted in Fig. 6 and its inset, respectively. It can be found that the maximum GMI ratio for the CWFC is 114% at 60 MHz, and its maximum $\Delta R/R$ ratio is 111% at 60 MHz. The CWCC reaches its maximum value of 116% at 600 kHz. Its maximum $\Delta R/R$ ratio achieves 205% at 2 MHz.
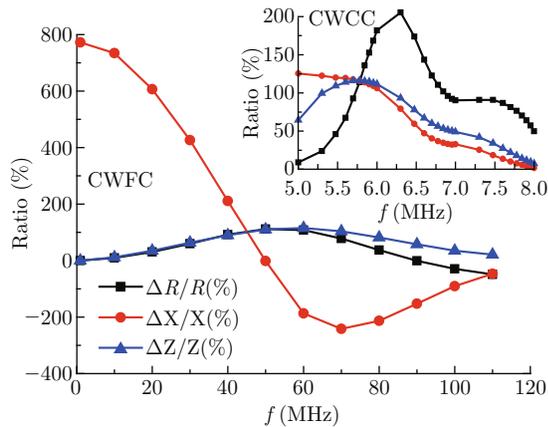
Fig. 6   Influence of frequency on $\Delta Z/Z$, $\Delta R/R$, $\Delta X/X$ of the CWFC, the inset shows frequency dependence of $\Delta Z/Z$, $\Delta R/R$, $\Delta X/X$ of the CWCC.

According to definition of impedance, $Z = R + iX$, the GMI ratio can be written as,

$$\Delta Z/Z = \frac{\sqrt{(R + \Delta R)^2 + (X + \Delta X)^2} - \sqrt{(R + X)^2}}{\sqrt{(R + X)^2}}$$

(4)

Therefore, GMI ratio does not only depend on $\Delta R/R$ and $\Delta X/X$, but also on the ratio of R to X. The resistivity of Cu core ($\sim 1.75 \times 10^{-8}$ $\Omega \cdot$m) is very small, R and X of the CWCC is comparable at low frequencies. Both $\Delta R/R$ and $\Delta X/X$ make comparative contribution to total $\Delta Z/Z$ ratio. When the value of $\Delta R/R$ is equivalent to $\Delta X/X$, $\Delta Z/Z$ ratio reaches its maximum value. However, the resistivity of ferromagnetic core ($\sim 1.47 \times 10^{-6}$ $\Omega \cdot$m) is much larger; two order magnitude higher than that of Cu. The values of R and X for CWFC are not comparable at low frequencies until high frequencies. Though the value of $\Delta X/X$ is much higher than that of $\Delta R/R$ at low frequencies, $\Delta R/R$ makes main contribution to $\Delta Z/Z$. The different electrical and magnetic properties of the core lead to the different electromagnetic interaction. This is also the reason that there is no much influence of the copper layer on the microwires.

Conclusions

In summary, the difference of the MI effect in two kinds of composite wires was investigated. The maximum MI ratio of 114% was achieved in CWFC at 60 MHz. Comparing to the microwires, the GMI effect of the CWFC strengths at low frequencies due to electromagnetic interaction. However, the effect is not remarkable. The CWCC shows better MI effect at lower frequencies, the maximum MI ratio of 116% was observed at 600 kHz. The results exhibit that the MI ratio reaches the maximum when both $\Delta R/R$ and $\Delta X/X$ make the comparative contribution to the total MI ratio. At low frequencies, $\Delta R/R$ has been obvious for

CWCC. Hence the CWCC has better MI properties at low frequencies.

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