Transactions of the Materials Research Society of Japan 29[4] 1701-1704 (2004)

Effect of Annealing on the GMI Response of Electroplated NiFe/Cu Composite Wire

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The influence of DC Joule annealing of electroplated $Ni_{80}Fe_{20}$/Cu composite wires on their giant magneto-impedance (GMI) effect is studied in this paper. Successive thermal treatments by DC Joule annealing with the current density ranging from 2.4 to 9.6 $\times 10^8$ A/m^2 were applied to the composite wires for a fixed annealing time of 1 minute to release the residual stresses. The results showed that the magneto-impedance (MI) effect of the composite wires can be greatly enhanced by DC Joule annealing. For electroplated 1.5 μm of $Ni_{80}Fe_{20}$ layer on a copper wire of 20 μm diameter, the optimum annealing current density was found to be 7.2×10^8 A/m^2 and from such annealing the MI ratio was increased from 637% to 1110%, a 74% increment. The optimum ac driving frequency for the GMI effect of the annealed wires under the influence of the annealing conditions in relation to the skin effect and permeability variation in the wires was investigated.

Keyword: Giant Magneto-impedance Effect, Composite Wires, Electroplating, Joule annealing

I. INTRODUCTION

The giant magneto-impedance (GMI) effect has attracted great interesting for its potential applications to high sensitivity micro magnetic sensors, since its discovery in amorphous wires in 1992 [1]. The GMI effect has been observed in homogeneous soft magnetic materials, such as amorphous wires, ribbons and thin films [2-3], and in inhomogeneous materials, such as composite wires and sandwiched thin films [4-5]. In contrast to the homogeneous materials, the skin effect is not the essential condition to obtain large GMI effect in composite structure materials. Normally their MI ratio is much larger than that of samples with the same dimensions and of similar homogeneous ferromagnetic materials. A study on the GMI effect of composite wires with a $Ni_{80}Fe_{20}$ layer electrodeposited on copper of 20 μm diameter indicated that the stress condition of the electroplated ferromagnetic materials of the composite wire affects the soft magnetic properties of the material and therefore affects the GMI effect of the composite wire. Therefore, the GMI effect of the composite wires may be enhanced by improving its soft magnetic properties through suitable heat treatment which releases the residual stresses in the ferromagnetic coating layer. In this study, a DC Joule annealing method has been utilized to heat treat electroplated NiFe/Cu composite wires. The results showed that the GMI effect of electroplated NiFe/Cu composite wires can be greatly enhanced.

II. EXPERIMENTAL DETAILS

Composite wire samples of 20 μm diameter copper core coated with a layer of $Ni_{80}Fe_{20}$ in thickness 1.5 μm and 8 cm in length were produced by electroplating at a constant temperature of 55°C. The plating current density was 2A/dm^2. The pH value of the plating electrolyte solution was kept constant at 3.4. The surface uniformity, thickness and composition of the plated layers were observed using SEM/EDX.

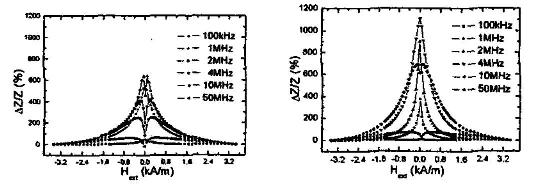
All the composite wire samples with 1.5 cm in length were annealed using a DC Joule annealing technique, in which under the protection of argon gas the composite wire has a DC current passing through it for 1 minute and then cools down under Ar gas. The average annealing current densities used were varied from 2.4 to 9.6 $\times 10^8$ A/m^2. MI measurements on the samples before and after annealing were carried out using a precision impedance analyzer (HP4294A). The RMS value of the ac driving current was kept constant at 20 mA, and its frequency was varied from 100 kHz to 50 MHz. The MI ratio was defined as impedance relative change:

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

where $Z(H_{ext})$ and $Z(H_{max})$ are the impedance values of a composite wire in MI effect testing under an arbitrary and maximum intensity of external magnetic field H_{ext}, respectively. The external magnetic field for the MI effect tests was generated by a Helmholtz Coil.

III. RESULTS AND DISCUSSION

Significant differences between the GMI effects in electroplated composite NiFe/Cu wires before and after DC Joule annealing can be seen from Fig. 1, where (a) and (b) show the MI effect curves tested under different ac driving frequencies for the same wire before and after annealing, respectively. Fig. 1(a) shows that in the wire before DC Joule annealing, the MI ratio in variation with the external magnetic field depended on the driving frequency of the ac current in the GMI effect test. At the DC driving frequency of 2 MHz, the MI ratio reached the maximum of 637%. For the wire with DC Joule annealing, Fig. 1(b) shows also that the MI ratio in variation with the external magnetic field depended on the driving frequency of the ac current in the GMI effect test. At the ac driving frequency of 4MHz, the maximum MI ratio was 1110%, which was a 74% increase compared to the maximum MI ratio in the wire before annealing.



(a) (b)

Fig 1.MI ratio in variation with external magnetic field for electroplated wire (a) before; (b) after, the DC Joule annealing.

The DC Joule annealing on the composite wires was successively carried out to study the influence of DC current density on the GMI ratio of the wire in the DC Joule annealing. Fig. 2 shows the MI effects relation to various annealing current densities. The MI ratios were measured at a testing frequency of 4MHz. It was found that there was an optimum current density for the DC Joule annealing, at which the annealed wire had the highest maximum MI ratio. The maximum MI ratios of the wires annealed in relation to the annealing current densities are shown in Fig. 3. It can be seen that the maximum MI ratio was in a slightly decreasing trend as the wires were annealed at lower current densities (below 4.8 $\times 10^8$ A/m^2). When the annealing current density was increased beyond 4.8 $\times 10^8$ A/m^2, the MI ratio started increasing. It reached the highest, 1110%, at the current density 7.2×10^8 A/m^2. As the annealing current density was further increased from 7.2×10^8 A/m^2, the MI ratio of the annealed wire dropped drastically.

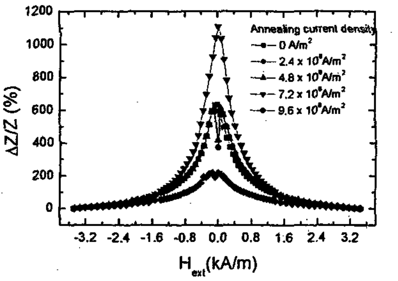


Fig 2. The effect of annealing current density on the MI ratio of DC Joule annealed electroplated composite wire in variation with an external magnetic field.

By classical electrodynamics theory, the impedance of wire samples was affected by the circumferential permeability. It has been also well documented that at low testing frequency, such as frequency below the relaxation frequency of domain wall motion, domain movement dominates the magnetization process and the total circumferential permeability monotonically decreases with respect to the external magnetic field. This explains why the MI ratio decreased with the external magnetic field H_{ext}, as shown in Fig. 1. With the increase in ac driving frequency, domain wall movements in the plated layer were nearly damped and thus the magnetization rotations dominated the magnetization process. Therefore, the circumferential permeability increased with the increase in the external field until the magnitude of the external field matched that of the anisotropy field, H_k. After the static circumferential permeability reached its peak, the dynamic circumferential permeability decreased with the increase in H_{ext}, till its saturation state. This also agreed well with the results of the MI tested at high frequencies, as shown in Fig. 1.

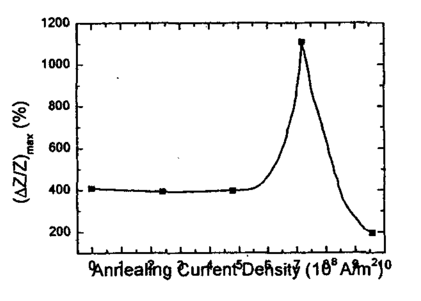


Fig 3. The effect of the annealing current density on the maximum MI ratio in the DC Joule annealed electroplated composite wires.

Before undergoing the DC Joule annealing, the plated layers of the composite wire samples contain residual stresses induced by the electrodepositing process. In annealing at the initial annealing current densities of 2.4×10^8 A/m^2 and 4.8×10^8 A/m^2, it was conjectured that there were tremendous inertia for the magnetic domains to rotate from their initial local anisotropy orientations to the circumferential anisotropy as induced by the annealing current. As a result, a larger crystalline magnetic anisotropy, k, was needed to rotate the domains, which were frozen in their initial directions, along the easy axis to the circumferential direction. This magnetic hardening also leaded to a slight drop in the MI ratio.

As the annealing current density was further increased, the maximum MI ratio increased steadily, till the annealing current density reached a peak, 7.2×10^8 A/m^2, at which the internal stresses was released by heating, which produced a lower constant of magnetostriction, λ_s, as well as a lower constant of crystalline magnetic anisotropy, k, for the $Ni_{80}Fe_{20}$ layer. The enhancement of the softer magnetic properties thus increased the MI ratio. Furthermore, the rotational factor of the magnetic susceptibility could be increased as the magnetocrystalline anisotropy constant k, magnetostriction constant λ_s and level of stresses in the material were decreased. This is precisely why heat treatment has long been recognized as an important tool for the improvement of magnetic properties of NiFe alloys.

Annealing at the current density beyond the optimal 7.2×10^8 A/m^2 resulted in a drastic decrease in MI ratio was due partially to the change in the phase composition of the solid solution and coarsening of the nanocrystalline grains, which caused a deterioration of the soft magnetic properties. This could be associated with the phase composition change or the ordering of NiFe alloy which increases the magnetic anisotropy constant. Another possible reason for the decline in MI ratio is the inter-diffusion between Ni atoms and Cu atoms above 250°C. This inter-diffusion might have caused the decay of the MI ratio by altering the magnetic properties of magnetic coating layer. It was reported [6] that at 250°C or above, Ni atoms preferentially diffuse into the Cu layer, thus increasing the resistivity of the material.

Fig. 4 displays the MI frequency spectrum of the composite wires before and after annealing. For all the wires with length of 15 mm in the MI testing it was observed that the maximum MI ratio increased with the increase of the ac driving frequency up to the highest, and then decreased with further frequency increases. For the wires annealed with the current density 4.8×10^8 A/m^2 or lower, the maximum MI ratios peaked at 2 MHz. For the wire annealed was at the current density 7.2×10^8 A/m^2, the maximum MI ratios peaked at 4 MHz. The maximum MI ratios of the wire annealed with current density 9.6×10^8 A/m^2 shows no obvious peak.

This spectrum can be explained by the circumferential permeability variation against driving frequency. At low frequency, the domain wall displacement dominated the magnetization. With the increase in the driving frequency, the dynamic permeability increased. At the frequency higher than the relaxation value, the magnetization processes was replaced by moment rotation, and the permeability dropped as a result of damping to the domain wall displacement.

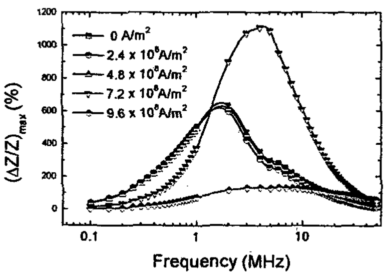


Fig. 4 MI spectrum of electroplated composite wire before and after annealing.

The maximum MI ratio appears when the circumferential permeability has begun to decrease. It is normally believed that the maximum MI ratio for such composite wires would appear at the condition when the skin penetration depth δ is of order of the dimensional size of the ferromagnetic materials. In this way if the conductivity of the NiFe layer is much larger than that of the copper core, the dimensional size is the radius of the copper core, and the same applies to the wires with and without annealing. However, the present results show that the optimum frequency shifted with the annealing parameters, which indicates the variation of the skin depth δ with the annealing parameters. Because the skin depth has relationship with permeability of the coating layer, hence, the shifting of the optimum frequency could be due to variation of the magnetic permeability and conductivity of the ferromagnetic layer. Another possible effect might come from the domain structure change during the annealing process.

IV. CONCLUSIONS

A DC Joule annealing method has been developed and tested for the enhancement of the GMI effect of electroplated NiFe/Cu composite wires. The results showed that the annealing makes great improvement on the MI ratio of the composite wires. The highest MI ratio of 1110% has been obtained, which was a 74% increase compared to the maximum MI ratio in the wire before annealing. The optimum conditions for the annealing method have also been studied. The results showed that for the tested wire samples there was an optimum annealing current density, at which the annealed wire has the highest MI ratio. The optimum ac driving frequency for the composite wire GMI sensor was found to be a function of the annealing current density which varies with the magnetic permeability and conductivity of the plated ferromagnetic layer.

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(Received October 8, 2003; Accepted December 19, 2003)