Magnetoelastic resonance enhancement of giant magnetoimpedance effect for Fe-based nanocrystalline alloy

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Abstract. Longitudinally driven giant magnetoimpedance (GMI) effect has been measured in Fe$_{73.5}$Cu$_{1}$Nb$_{3}$Si$_{13.5}$B$_{9}$ ribbons, and the enhancement of GMI effect using magnetoelastic resonance was investigated. The results showed that at a certain driven frequency when magnetoelastic resonance occurred, there was a great enhancement of the impedance of the element and MI effect. For the ribbon of 1.0 cm in length annealed at 480°C, the maximum MI ratio of 10 906% was achieved at the frequency of 214 kHz. The maximum sensitivity reached up to 5 155%/Oe, which was almost 40 times higher than that observed in traditional MI measurements. The results demonstrated that the enhanced magnitude of MI effect mainly depended on magnetoelastic coupling coefficient $k$. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3094747]

Subject terms: longitudinally driven giant magnetoimpedance; magnetoelastic resonance; magnetoelectric coupling; nanocrystalline ribbons.

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1 Introduction

Giant magnetoimpedance (GMI) effect has attracted much attention over the past 16 years because it has potential applications in magnetic sensors and recording heads with high sensitivity and quick response.\textsuperscript{1–4} Much effort has been developed to improve the MI sensitivity, such as annealing treatment,\textsuperscript{2} altering material geometrical structure,\textsuperscript{3} or adding an inductor-capacitor (LC) resonance in measuring system.\textsuperscript{4}

In this work, a new method using magnetoelectric resonance is introduced to enhance GMI effect. Longitudinally driven GMI effect for Fe-based amorphous and nanocrystalline ribbons was measured.\textsuperscript{5} Magnetoelectric resonance of the ribbons occurred via magnetostriction at a certain driven frequency. As a result, the impedance was greatly enhanced and a large GMI effect could be obtained. A maximum MI ratio of 10 906% was achieved at 214 kHz for the ribbon of 1.0 cm in length annealed at 480°C. The maximum sensitivity reached up to 5 155%/Oe, which was almost 40 times higher than that observed in traditional MI measurements. Some discussion about the dependence of MI on magnetoelectric resonance is given in Sec. 3.

2 Experimental Details

The amorphous Fe$_{73.5}$Cu$_{1}$Nb$_{3}$Si$_{13.5}$B$_{9}$ ribbons, 0.8-mm wide and 25-$\mu$m thick, were fabricated by single-roller quenching technique. Samples of different lengths (0.5, 0.8, 1.0, 1.5, 2.0 cm) were prepared and annealed under different temperatures (460°C, 480°C, 510°C, 540°C) for 30 min and cooled down to room temperature in nitrogen atmosphere. In MI measurements, the sample was placed in a small solenoid 1.4 mm in diameter. The sample and the solenoid as a whole formed an ac equivalent impedance component. An HP4294A impedance analyzer (Agilent Technologies, Santa Clara, California) was used to measure the impedance of the MI elements. The alternating current $i$ was kept at 200 $\mu$A, and the driven frequency ranged from 1 kHz to 40 MHz. The MI ratio was defined as

$$\frac{\Delta Z}{Z} (%) = \frac{Z(H_{\text{ex}}) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \times 100,$$ \hspace{1cm} (1)

where $Z(H_{\text{ex}})$ and $Z(H_{\text{max}})$ are the impedance values of the sample under an external magnetic field $H_{\text{ex}}$ and under the maximum external magnetic field $H_{\text{max}}$, respectively. The external field was provided by a pair of Helmholz coils. The maximum external magnetic field used in the measurement, $H_{\text{max}}$, was 120 Oe.
3 Results and Discussion

Figure 1 shows the dependence of MI ratio on driving frequency for ribbons of different lengths annealed at 540°C. Roughly, the MI curves exhibit a mountainlike shape, and the MI ratio increases as the length of ribbon increases. An MI ratio of 2280% was achieved for a 2-cm long ribbon at 230 kHz. It is worth noting that each MI curve superposes a sharp peak at optimal frequency and enhances the MI effect. An MI ratio of 2533% was obtained at optimal frequency of 125 kHz for the ribbon of 2.0 cm. This peak originates from the magnetoelastic resonance; detailed explanations have been reported in Ref.6. The optimal frequency corresponds to the enhancement peak in the MI ratio increases as the length of ribbon increases. An MI ratio of 2280% was achieved for a 2-cm long ribbon at 100 kHz, the largest MI effect was obtained in the ribbon annealed at 540°C, due to its maximum effective permeability. When the frequency increases to around 220 kHz, the distinct enhancement peaks appear in the MI curves. A maximum MI ratio of 10906% was observed for the ribbon annealed at 480°C at 214 kHz, whereas an MI ratio of 3000% was achieved for the ribbon annealed at 540°C. According to the previous discussion and Fig. 1, the MI enhancement arises from the magnetoelastic resonance. Here, the magnetoelastic coupling coefficient $k$ plays an important role in magnitude of the MI enhancement. The higher the magnetoelastic coupling coefficient $k$, the larger the resonance peak would be, so that a higher MI ratio could be achieved. In theory, magnetoelastic coupling coefficient $k$ can be given by the expression

$$k^2 = a\chi \left( \frac{\partial M}{\partial M} \right)^2 E = \frac{9 E \lambda_S^2}{4 \pi M_S^2 \mu_0 M} \left( M \right)^2,$$

where $E$ is the Young’s modulus, $M$ is the magnetization, $M_S$ is the saturation magnetization, $\mu_0$ is the permeability, and $\lambda_S$ is the saturation magnetostriction coefficient. For the ribbon annealed at 480°C, because the grains of $\alpha$-Fe(Si) is just precipitated in the amorphous matrix, the inherent stress and the saturation magnetostriction are the largest, resulting in the largest magnetoelastic coupling coefficient $k$. For the ribbon annealed at 540°C, although it has the largest effective permeability, $k$ is still the lowest due to the smallest magnetostrictive coefficient. In addition, the enhancement of MI effect has not been observed in the amorphous ribbon due to small $k$.

Figure 2 shows the optimal frequency dependence on the length of the ribbons, where the optimal frequency corresponds to the enhancement peak in Fig. 1. The full line is the fitting curve drawn from Eq. (2). It can be seen that the frequency values agree well with the fitting curve, testifying in reverse that the enhancement of MI effect arises from the magnetoelastic resonance.

To investigate the relation between the enhanced magnitude of MI effect and the magnetic properties, the GMI effect of the ribbons of 1.0 cm in length annealed under different temperatures was investigated, shown in Fig. 3. It can be seen that when the driven frequency is below 100 kHz, the largest MI effect was obtained in the ribbon annealed at 540°C, due to its maximum effective permeability. When the frequency increases to around 220 kHz, the distinct enhancement peaks appear in the MI curves. A maximum MI ratio of 10906% was observed for the ribbon annealed at 480°C at 214 kHz, whereas an MI ratio of 3000% was achieved for the ribbon annealed at 540°C. According to the previous discussion and Fig. 1, the MI enhancement arises from the magnetoelastic resonance. Here, the magnetoelastic coupling coefficient $k$ plays an important role in magnitude of the MI enhancement. The higher the magnetoelastic coupling coefficient $k$, the larger the resonance peak would be, so that a higher MI ratio could be achieved. In theory, magnetoelastic coupling coefficient $k$ can be given by the expression

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Figure 4 shows the magnetic field dependence of the MI ratio for the ribbon of 1.0 cm at different driving frequencies.
cies. At the resonance frequency of 214 kHz, the MI ratio and the sensitivity reached up to 10 906% and 5 155%/Oe, respectively. However, at 637 kHz, when the frequency regime is far from the magnetoelastic resonance frequency, the maximum MI ratio was 867% and the sensitivity obtained was only 127%/Oe. It is likely that sensors based on this magnetoelastic resonance could have a higher sensitivity. Work toward its sensor application is under way.

4 Conclusions

In this paper, magnetoelastic-resonance-type MI effect was investigated in Fe-based nanocrystalline and amorphous ribbons. The results demonstrated that magnetoelastic coupling coefficient $k$, which could be tailored by varying annealing treatment and altering the length of the samples, was a critical parameter for the enhancement of MI effect. An MI ratio of 10 906% and a sensitivity up to 5 155%/Oe were achieved for the ribbon of 1.0 cm in length annealed at 480°C.

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References


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