The effect of magnetoelastic interaction on the GMI behaviour of Fe-, Co- and Co–Fe-based amorphous wires

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Abstract

The giant magnetoimpedance is the sensitive change in ac impedance value with the application of dc magnetic field when ac current passes through the sample. In the present work GMI properties of positive (Fe 77.5 Si 7.5 B 15 ), negative (Co 72.5 Si 12.5 B 15 ) and nearly zero ((Co 94 Fe 6 ) 72.5 Si 12.5 B 15 ) magnetostrictive amorphous wires have been studied. The result indicates that the magnetostriction constant plays an important role in GMI property. The maximum GMI ratio (330%) and maximum field sensitivity (7% per A/m) are observed in (Co 94 Fe 6 ) 72.5 Si 12.5 B 15 amorphous wire. The frequency response of the GMI characteristics of the above alloys has been measured and zero magnetostrictive (Co 94 Fe 6 ) 72.5 Si 12.5 B 15 material showed better frequency response.

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1. Introduction

Micromagnetic sensors based on transport properties with high sensitivity and quick response are in great demand for establishing advanced intelligent measurement and control system for modern technology. Due to its sensitivity in the wide range of field (10^{-5} to 1 A/m), giant magnetoresistive (GMR) materials are very promising for sensor applications. As GMR materials are prepared in the form of thin film by photolithography fabrication method, which is very advanced for the development of semiconductor technology, miniaturisation of the sensor is possible using MR elements [1]. However, the magnetic saturation field for the MR materials is high and the field sensitivity is very low (10^{-2} per A/m). Besides, there are hysteresis and temperature instability problem in MR materials. To overcome the above problems attempts have been made to search for new materials that have low hysteresis loss and better temperature stability. Since 1993 considerable attention has been focused on the study of giant magnetoimpedance (GMI) behaviour in amorphous materials as a new-generation for micromagnetic sensors of high performance [2–6]. The interpretation of the GMI behaviour of the amorphous materials requires a deep understanding of magnetoelastic properties and their dependence on the dynamic magnetism.

The GMI behaviour of the materials depends on soft magnetic properties of the surface layer, domain configuration, magnetic anisotropy, magnetoelastic properties and mode of magnetisation. It has been observed that the nature of GMI is very much dependent on the shape and the magnetoelastic anisotropy of the materials and hence the materials of similar compositions but in different shapes, like wires [7–8,10,12], ribbons [9,14], sandwiched films [11], crystalline mumetal [13] exhibited different values in GMI. The objective of the paper is to find the influence of the magnetoelastic interaction on the GMI characteristics of the materials. To do so, three different wire shaped samples having different magnetostrictive constant have been chosen by varying their composition. The materials studied in this work were Fe 77.5 Si 7.5 B 15, Co 72.5 Si 12.5 B 15, and (Co 94 Fe 6 ) 72.5 Si 12.5 B 15 having magnetostrictive constant (λs) 32 × 10^{-6}, −2.6 × 10^{-6} and −0.08 × 10^{-6}, respectively [15].

2. Experimental

Amorphous wires of diameter 125 µm prepared by in-water quenching apparatus. About 10 cm long sample has been placed along the axis of a Helmhotz coil for the GMI measurement. The block diagram of the experimental

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set-up shown in Fig. 1. The impedance was measured by four probe technique
where the driving ac current ($I_{ac}$) of amplitude 5 mA of frequency in the range
of 1–10 MHz was sent through the current probe and voltage across the voltage
probe was measured. A spectrum analyser (Agilent-4401B) was used for
impedance measurement, which was connected to a computer data acquisition
system. A dc magnetic field parallel to the axis of the sample was applied by the
Helmholtz coil. The sample axis was placed perpendicular to the earth’s magnetic
field to minimize its effect on the sample. The result of the experimental data
has been plotted as the percentage change of magnetoimpedance with applied
magnetic field and is expressed as

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

where $H_{max} = 10$ kA/m, the maximum applied dc field.

3. Results

The field dependence of GMI behaviour of Fe$_{77.5}$Si$_{7.5}$B$_{15}$ sample at various frequencies of driving ac current having amplitu-
de of 5 mA is shown in Fig. 2. The as-cast sample showed maximum GMI ratio of 22% at $f = 1$ MHz and the GMI ratio
decreased monotonically with the increase of the dc field. The maximum GMI value was obtained at $H_{dc} = 0$. As frequency
increased the GMI ratio decreased and at the same time the single peak also broadened, leading to an apparent increased in
the magnetic field, which saturated the impedance value. At fre-
quency above 5 MHz the shape of the GMI profile changed over
from single peak behaviour to two peaks structure when con-
sidered for both positive and negative halves of the external dc
magnetic field ($H_{ex}$). As the frequency was increased more the
peaks were shifted towards the higher magnetic field and GMI
ratio was decreased.

Fig. 3 shows the axial field dependence ($H_{ax}$) of the GMI
ratio as a function frequency of the driving ac current ($I_{ac}$) of
amplitude 5 mA for the Co$_{72.5}$Si$_{12.5}$B$_{15}$ sample. The single peak
behaviour was observed. With the increase of frequency, the zero
field peak decreased and hence GMI ratio decreased. The max-
imum GMI ratio obtained was 88% at $f = 1$ MHz. With increase
Fig. 4. Field dependence of GMI ratio ($\Delta Z / Z$) of (Co$_{94}$Fe$_6$)$_{72.5}$Si$_{12.5}$B$_{15}$ wire at different frequencies.

of the applied dc field GMI ratio decreased, showing a minimum and again it increased showing a broad maximum around 1.6 kA/m dc magnetic field. 

Fig. 4 shows the variation of GMI ratio with applied dc magnetic field ($H_{ex}$) for different frequencies with the driving ac current of amplitude 5 mA. GMI ratio increased with the application of dc field showing a peak and then decreased with further increase of field. The maximum GMI ratio was observed close to 330% at $f = 1$ MHz. The peaks were observed at ±16 A/m which is a measure of circular anisotropy field of the sample. GMI ratio decreased with increasing frequency. At $f = 9$ MHz the GMI ratio decreased to 35% from 330% at $f = 1$ MHz. As frequency increased the GMI peak shifted to the higher $H_{ex}$ value and hence the circular anisotropy field increased.

The variation of the peak value of GMI ratio (GMI$_{max}$) with frequency of the ac driving current for three measured wires is shown in Fig. 5. GMI$_{max}$ initially increased with the frequency for Fe$_{77.5}$Si$_{12.5}$B$_{15}$ (Fig. 5(I)) and attained maximum of about 22% at 6 MHz and started decreasing. The maximum GMI ratio (GMI$_{max}$) decreased with frequency and attained minimum value of 20% at 6 MHz for Co$_{72.5}$Si$_{12.5}$B$_{15}$ as shown in Fig. 5(II). At higher frequency (8 MHz for Fe$_{77.5}$Si$_{12.5}$B$_{15}$ and 6 MHz for Co$_{72.5}$Si$_{12.5}$B$_{15}$) GMI$_{max}$ increased which was due to resonance effect that caused abrupt change to the impedance of the sample. The variation of GMI$_{max}$ with frequency for (Co$_{94}$Fe$_6$)$_{72.5}$Si$_{12.5}$B$_{15}$ is shown in Fig. 5(III). In this case slow variation of GMI$_{max}$ with frequency was observed up to 5 MHz and then a rapid decrease was observed. No resonant effect was found for this alloy.

The field sensitivity which is the slope near the zero field region of external field dependence of GMI ratio curve, is defined as $\eta = \left(\Delta Z / Z\right) / \Delta H_{ex}$, and is plotted against frequencies for the three measured alloys as shown in Fig. 6. No significant variation in field sensitivity with frequency was observed for Fe$_{77.5}$Si$_{12.5}$B$_{15}$ alloy, which also showed low GMI ratio. In case of Co$_{72.5}$Si$_{12.5}$B$_{15}$ alloy the field sensitivity decreased with frequency whereas very low variation up to 4 MHz frequency was observed for (Co$_{94}$Fe$_6$)$_{72.5}$Si$_{12.5}$B$_{15}$ alloy. Above 4 MHz the field sensitivity of (Co$_{94}$Fe$_6$)$_{72.5}$Si$_{12.5}$B$_{15}$ alloy dropped rapidly up to 7 MHz and remained constant. The maximum field sensitivity for this alloy was 7% per A/m observed at $f = 2$ MHz.

4. Discussion

When an ac current of amplitude $I_{ac}$ passes through the wire, a transverse magnetic field of strength $H_B = I_{ac} r / (2 \pi r_0^2)$ developed, where $r_0$ = wire radius, $r$ = distance measured from the axis of the centre. This time varying magnetic field changes the circular components of the magnetisation and induces a voltage, which is proportional to the circular permeability of the sample and strongly dependent on the circular anisotropy of the materials. When an additional dc field is applied along the wire axis, the effective magnetic field on the wire changes. Such change influences the circular permeability of the material in a greater extent resulting in a large change in magnetoresistive value. This effect is known as giant magnetoimpedance (GMI) effect. GMI effect is very prominent at high frequencies of the ac driving field where skin effect plays an important role in magnetic
circular permeability ($\mu > 100$ kHz) the application of dc magnetic field changes the radius $r$ of a thin sheath near the surface of the sample. From the classification of eddy current and consequently, the current flows through the wire through which the current flow is reduced due to the generation of eddy current and the corresponding circular permeability term also reduces. This ac circular permeability is in generally a non-diagonal complex tensor. Keeping into consideration of rotational magnetisation process at high frequency, the ac circular permeability tensor can be expressed as

$$\mu_a = 1 + 4\pi \cos^2(\theta) \chi_1$$

(5)

where $\theta$ is the angle between the saturation magnetisation $M_s$ and the wire axis and $\chi$ is the susceptibility tensor which can be expresses as [20]

$$\chi = \chi_1 - 4\pi \chi_2 \frac{1}{1 + 4\theta^2}$$

(6)

In Eq. (6), the parameters $\chi_1$, $\chi_2$ and $\chi_3$ are the diagonal and off-diagonal components of the ac rotational susceptibility tensors written in the coordinate system with $z$-axis parallel to $M_s$. Considering the anisotropy axis is directed at angle $\alpha$ with respect to the wire axis, the susceptibility tensor components can be expressed as

$$\chi_1 = \frac{\omega g (\omega_1 - j\omega \tau)}{\Delta + \omega_2 (\omega_1 - j\omega \tau)}$$

$$\chi_2 = \frac{\omega g (\omega_1 - j\omega \tau)}{\Delta},$$

$$\chi_3 = \frac{\cos \theta}{\Delta},$$

(7)

$$\Delta = (\omega_1 - j\omega \tau)\omega_2 - \omega^2,$$

$$\omega_1 = \gamma [H_{kz} \cos \theta + H_0 \cos 2(\alpha - \theta)],$$

$$\omega_2 = \gamma [H_{kz} \cos \theta + H_0 \cos^2(\alpha - \theta)],$$

$$\omega_3 = \lambda M_s,$$

where $\gamma$ is the gyromagnetic constant, and $\tau$ is the relaxation parameter. Eq. (7) shows that the rotational ac susceptibility decreases with increasing frequency and it can be derived [18] from the above equation that real part of the susceptibility has a maximum at a position closer to $H_{kz} = 1$, where $H_k$ is the anisotropy field. However, near the ferromagnetic resonance frequency, ac rotational susceptibility loses its field sensitivity.

The wires with negative magnetostriction constant like $Co_{72.5}Si_{12.5}B_{15}$ and $Co_{64Fe_{20}}Si_{12.5}B_{15}$ have circular domain structure with longitudinal direction as the hard magnetic axis. When a dc axial field ($H_{ex}$) is applied to such wires the magnetisation in each domain rotates towards the axis, increasing the circular permeability ($\mu_\phi$) and thus increasing the GMI ratio. The maximum permeability is reached for a static applied field that balances the transverse anisotropy field ($H_{kz}$) [18], the point where the GMI ratio has maximum value. Further increase of $H_{ex}$ leads to the situation where the circular magnetisation process becomes dominated by magnetisation rotation and therefore circular permeability decreases and hence the GMI ratio of
the sample decreases, reaching a constant and very low value. Thus, domain rotation takes place by application of small external field ($H_{ex}$) to $H_{0}$ in the longitudinal direction, the GMI behaviour shows two peaks display at $±H_{k}$. This explains the two-peak (TP) behaviour of $\text{Co}_{94}\text{Fe}_{6}\text{Si}_{12.5}\text{B}_{15}$ wire (Fig. 4) which has a low magnetostrictive constant and thus high circular anisotropy energy. Such a finite field is ascribed to the inherent (although may be small) irreversible component of the axial magnetisation process [22] and the internal stress induced during the rapid quenching process. The magnetoelastic energy associated with the sample can be expressed [23,24] as

$$w_{M} = -\frac{1}{2} \sigma_s \left( \sigma_x^2 + \sigma_y^2 + \sigma_z^2 \right)$$  \hspace{1cm} \text{(8)}$$

where $\sigma_x$ is the component of the residual stress tensor, $\sigma_s$ is the component from the unit magnetisation vector and $\lambda_s$ is the saturation magnetisation constant. The residual stress distribution of the amorphous wire [25] shows $\lambda_s = 20$ (CoFeSiB) wire which has high positive magnetostrictive constant ($32 \times 10^{-6}$) exhibits easy axis magnetisation in the core but radial in the shell. Hence, it requires a high dc field to orient the domains resulting in very low GMI ratio. The $\text{Co}_{94}\text{Fe}_{6}\text{Si}_{12.5}\text{B}_{15}$ wire with large negative magnetostrictive value changes [26] and it becomes nearly zero ($0.08 \times 10^{-4}$) in $\text{Co}_{72.5}\text{Si}_{12.5}\text{B}_{15}$ alloys. Hence, the magnetoelastic energy of this material is very low and domains are not oriented in any preferential direction. Thus, domain rotation takes place by application of small external field resulting in large GMI ratio.

5. Conclusion

The frequency response of GMI properties for positive, negative and nearly zero magnetostrictive amorphous wires were measured and analysed. Among the measured alloys nearly zero magnetostrictive ($\text{Co}_{94}\text{Fe}_{6}\text{Si}_{12.5}\text{B}_{15}$) amorphous alloy showed excellent GMI behaviour with the maximum GMI ratio as 330%. The field sensitivity of this alloy was 7% per A/m, which is very high compared to other measured alloys like $\text{Fe}_{77.5}\text{Si}_{7.5}\text{B}_{15}$ and $\text{Co}_{72.5}\text{Si}_{12.5}\text{B}_{15}$. Lowering of magnetostrictive constant with the addition of Fe in $\text{Co}_{72.5}\text{Si}_{12.5}\text{B}_{15}$ alloy makes the anisotropy energy of the alloy low resulting in excellent response of GMI to the external magnetic field. Slow variation of GMI ratio with the driving frequency upto 4 MHz for ($\text{Co}_{94}\text{Fe}_{6}\text{Si}_{12.5}\text{B}_{15}$) also suggests that the material can be used for a wide frequency range. High GMI ratio, high field sensitivity and wide range of operating frequency makes the materials a suitable candidate for the magnetic sensors.

References


