# Highly sensitive giant magnetoimpedance in a solenoid containing FeCo-based ribbon*

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The highly sensitive giant magneto-impedance effect in a solenoid containing a magnetic core of $Fe_{36}Co_{36}Nb_4Si_{4.8}B_{19.2}$ (FeCo-based) ribbon under a weak magnetic field (WMF) is presented in this paper. The FeCo-based amorphous ribbon is prepared by single roller quenching and annealed with Joule heat in a flowing nitrogen atmosphere. The giant magnetoimpedance effect in solenoid (GMIES) profiles are measured with an HP4294A impedance analyzer. The result shows that the GMIES responds to the WMF sensitively (as high as 1580 %/A·m$^{-1}$). The high sensitivity can be obtained in a moderate narrow range of annealing current density (30–34 A/mm$^2$) and closely depends on the driven current frequency. The highest sensitivity (1580 %/A·m$^{-1}$) is obtained when the FeCo-based amorphous ribbon is annealed at 32 A/mm$^2$ for 10 min and then driven with an alterning current (AC) at the frequency of 350 kHz. The highly sensitive GMIES under the WMF may result from the multiple magnetic-anisotropic structure, which is induced by the temperature gradient produced during Joule-heating the ribbon.

**Keywords:** giant magneto-impedance, FeCo-based ribbon, Joule heat, weak magnetic field

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## 1. Introduction

Recently, much attention has been paid to the development of new magnetic materials in order to acquire a higher magnetic sensitivity of giant magnetoimpedance (GMI) in a weak magnetic field (WMF),[1−5] which is promising for the development of weak magnetic-field sensors. In the past few years, many studies of the asymmetric giant magnetoimpedance (AGMI) have been reported.[6−9] Rosales-Rivera *et al.*[10] have reported the three-peak GMI of an FeCrNbCuSiB amorphous ribbon. Zhukova *et al.*[11] have reported the AGMI of amorphous glass-coated micro-wires. They can sensitively respond to a weak magnetic field linearly when the magnetic field is lower than the second peak. Those previous studies have led to new ideas for designing and developing highly sensitive WMF sensors. But a fly in the ointment is that the sensitivity will drop off when the magnetic-field sweep step is over the second peak of their GMI profiles,[10] and it will limit the application of the WMF sensor. The giant magnetoimpedance effect in solenoid (GMIES) of the $Fe_{36}Co_{36}Nb_4Si_{4.8}B_{19.2}$ (FeCo-based) amorphous ribbon annealed with Joule-heat in flowing nitrogen atmosphere can sensitively respond to a WMF. It not only has a higher magnetic sensitivity (as high as 1580 %/A·m$^{-1}$) in the WMF, but also does not lower its sensitivity, as shown in Ref. [10]. A detailed study of the behaviors of the GMIES containing FeCo-based ribbon versus the annealing current density and the driving current frequency is presented in this paper.

## 2. Experimental details

The FeCo-based amorphous ribbons (0.2 mm in width and 45 μm in thickness) were prepared by single

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roller quenching, and then were cut into 70 mm long samples. The samples were annealed in flowing nitrogen atmosphere by direct-current (DC) heating with a current density in the range of 0–53 A/mm$^2$ for 600 s. As shown in Fig. 1, a ribbon with a length of 15 mm was placed in a small solenoid (100 turns, 0.3 mm in diameter, and 11 mm in length), forming a magnetic core solenoid (MCS). The impedance of the MCS was measured from the two electrodes at the ends of the solenoid with an HP4294A impedance analyzer. The driving alternating current (AC, its peak was 10 mA) was supplied to the solenoid, which produced an AC longitudinal driving field for the ribbon sample inside the solenoid. The external magnetic field was applied in the direction parallel to the axis of the ribbon, and the solenoid was generated by a pair of Helmholtz coils with the axis perpendicular to the Earth's magnetic field in order to minimize its influence.

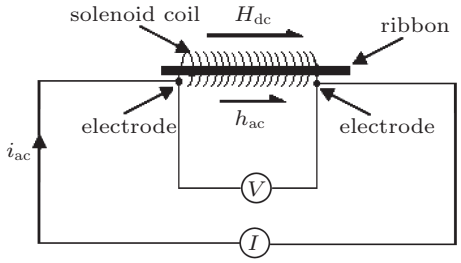



**Fig. 1.** Diagrammatic sketch of the MCS.

The GMIES ratio is defined[12] as

$$\Delta Z/Z = \left(\frac{Z_{H_{ex}} - Z_{H_{max}}}{Z_{H_{max}}}\right) \times 100\%, \qquad (1)$$

where $Z_{H\,max}$ is the impedance under the maximum external magnetic field, and $Z_{H\mathrm{ex}}$ is the impedance under any external magnetic field in the range from zero to maximum. The maximum external magnetic field was 1628 A/m.

# 3. Results and discussion

## 3.1. Tip-peak-like GMIES profiles

Figure 2 shows the profile of the GMIES containing the FeCo-based ribbon annealed at 32 A/mm$^2$ for 600 s and driven by 400 kHz alternating current (the peak is 10 mA). In Fig. 2, the GMIES profile shows a tip peak on the top. The tip peak shows that the GMIES responds to the WMF sensitively (1380 %/A·m$^{-1}$). It is called the tip-peak giant magneto-impedance (TGMI) effect. The height of the tip-peak $\Delta_T$, the height of the foundational curve $\Delta_F$, the full width at half maximum of the tip-peak $\Delta H_T$, and the full width at half maximum of the foundational curve $\Delta H_F$ are shown in Fig. 2. The sensitivity of the tip peak is defined as

$$\xi_T = \frac{\Delta_T}{\Delta H_T}. \qquad (2)$$

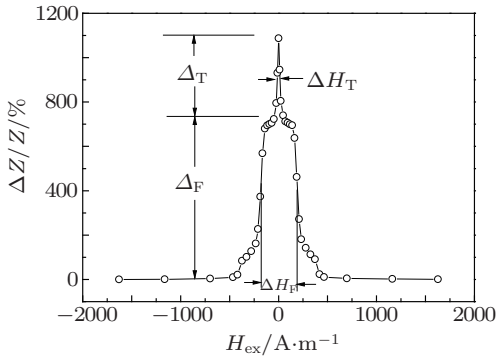



**Fig. 2.** The TGMI profile.

## 3.2. Dependence of TGMI on the annealing current

Figure 3 shows the representative profiles of the GMIES containing the FeCo-based ribbon annealed at different current densities. Curve A is the profile of the as-case GMIES, while curve B–E are the profiles of the GMIES annealed for 600 s at the DC densities of 28 A/mm$^2$, 32 A/mm$^2$, 38 A/mm$^2$, and 47 A/mm$^2$, respectively, and the driven current frequency is 400 kHz. In curve A, there is a plateau on the top of the GMIES profile (the maximum GMIES ratio is 1192.5 %) located in the WMF region from -200 A/m to 200 A/m. Additionally, the width of the lower part ($\Delta Z/Z < 600\%$) is twice that of the upper part ($\Delta Z/Z > 600\%$). Compared to curve A, the top of curve B becomes smooth, and the maximum GMIES ratio decreases to approximately half that of curve A. In curve C, a tip peak appears in the foundational part, which is similar to curve B. The tip peak shows that the GMIES responds to the WMF sensitively (1380 %/A·m$^{-1}$), which is the tip-peak giant magneto-impedance effect. In curve D, the GMIES ratio rises to the maximum (2027.8%), which is apparently higher than the maxima of the other curves, but the tip peak vanishes. In curve E, the GMIES ratio decreases significantly and shows the asymmetrical GMI effect.

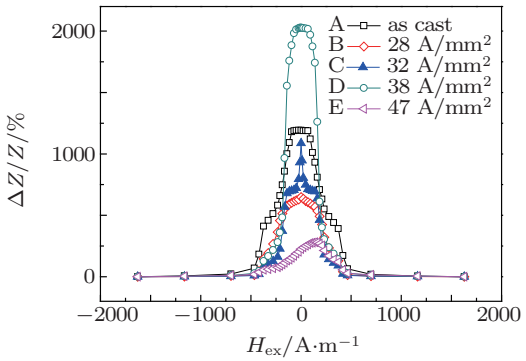



**Fig. 3.** (colour online) Profiles of GMIES containing FeCo-based ribbon annealed at various DC densities.

Figure 4 shows the full width at half maximum of the GMIES curve $\Delta H_F$ and the maximum GMIES ratio $(\Delta Z/Z)_{max}$ versus the annealing current density. Curve A shows that $\Delta H_F$ decreases down to 38 A/mm$^2$ and then increases with the annealing current density increasing. The $(\Delta Z/Z)_{max}$ shown in curve B decreases down to 27 A/mm$^2$ and then increases with the annealing current density increasing. It oscillates slightly near 32 A/mm$^2$, reaches the maximum value at 38 A/mm$^2$, and then decreases rapidly after the maximum. The minimum of $\Delta H_F$ and the maximum of $(\Delta Z/Z)_{max}$ appear at the same point of 38 A/mm$^2$.

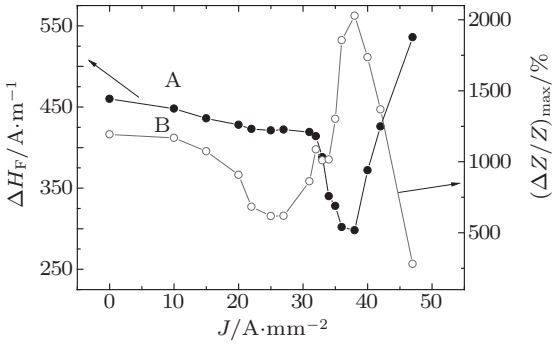



**Fig. 4.** The $\Delta H$ and $(\Delta Z/Z)_{max}$ versus annealing current density.

Figure 5 shows $\Delta_T$ versus the annealing current density. There is a sharp peak, which means that the tip peak appears only in a narrow annealing current density range (30–34 A/mm$^2$). The top of the tip peak is at the point of 32 A/mm$^2$. The annealing current density range, in which the tip peak appears, corresponds to the $(\Delta Z/Z)_{max}$ oscillation range shown in curve B of Fig. 4, and does not correspond to the point of maximum $(\Delta Z/Z)_{max}$ or minimum $\Delta H_F$ shown in Fig. 4. It indicates that the TGMI effect can be obtained only in a moderate narrow range of the annealing current density (30–34 A/mm$^2$) before the customary GMIES reaches the maximum.

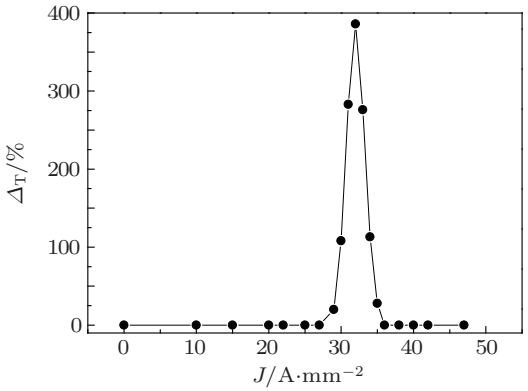



**Fig. 5.** The $\Delta_T$ versus annealing current density.

## 3.3. Dependence of TGMI on frequency of the driving current

Figure 6 shows the TGMI curves at different frequencies of the driving current. The results show that the TGMI effect is sensitively dependent on the driving current frequency. Figure 7 shows the tip-peak sensitivity $\xi_T$ (defined in Eq. (2)) versus the driving current frequency. The $\xi_T$ increases with the driving current frequency increasing up to 350 kHz and then decreases to zero at 700 kHz. The maximum sensitivity $\xi_{Tmax} = 1580$ %/A·m$^{-1}$ appears at 350 kHz.

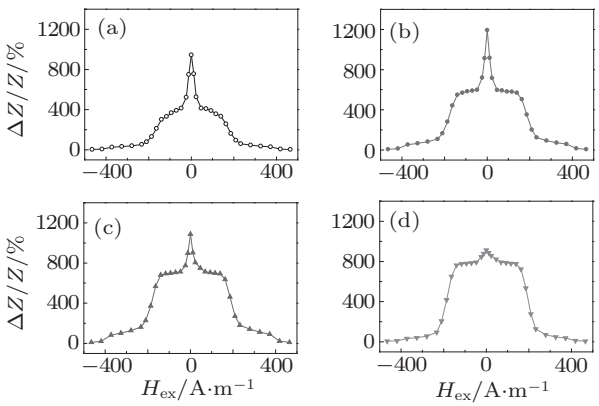



**Fig. 6.** TGMI curves at the driving current frequencies of (a) 200 kHz, (b) 350 kHz, (c) 400 kHz, and (d) 500 kHz.

To verify whether the TGMI effect reduces the sensitivity in the WMF as the three-peak GMI does[10] when the field scan step becomes larger, the TGMI curve of the FeCo-based ribbon annealed at 32 A/mm$^2$ at the scan steps ($r$) of 23.3 A/m, 46.6 A/m, 69.9 A/m, and 93.2 A/m were measured, and the results are shown in Fig. 8. When the driven current frequency is 300 kHz, each of the TGMI curves with different $r$

has a tip peak in the WMF region. The $\Delta_T$ does not reduce with the increasing $r$.

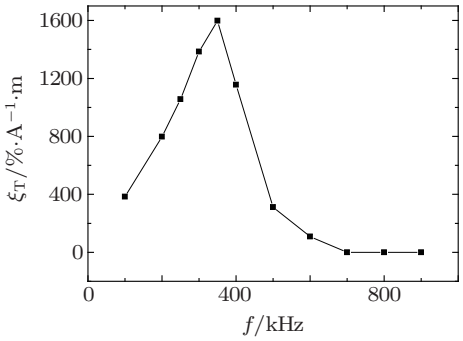



**Fig. 7.** Tip-peak sensitivity $\xi_T$ of the MCS containing FeCo-based ribbon annealed at 32 A/mm$^2$ versus the driving current frequency.

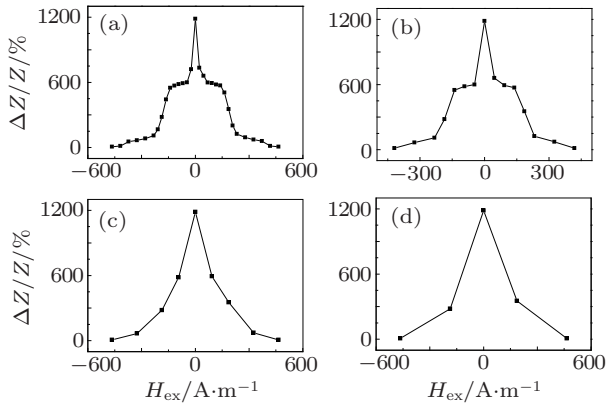



**Fig. 8.** TGMI curves for external magnetic field scan steps of (a) 23.3 A/m, (b) 46.6 A/m, (c) 69.9 A/m, and (d) 93.2 A/m.

## 4. Mechanism of TGMI

Figure 9 shows that the ribbons do not crystallize observably when the annealing current density is lower than 35 A/mm$^2$. It means that the ribbon is still in the amorphous phase when the TGMI effect arises. Many studies have reported that the magnetic anisotropy influences the GMI effect.[13−16] The magnetic anisotropy may change during Joule-heating the FeCo-based ribbon, however the microstructure change cannot be observed in the XRD diffraction spectra. Figure 10 shows the TGMI effect profiles of the MCS containing FeCo-based ribbon, which is Joule-heated at 32 A/mm$^2$ for 10 min and corroded from 45 μm to 5 μm by 16.7% HCl solution. A comparison of Figs. 10(a)–10(d) shows that the magnetic anisotropy[13] in the FeCo-based ribbon decreases as the residual thickness of the FeCo-based ribbon is reduced by the corrosion.

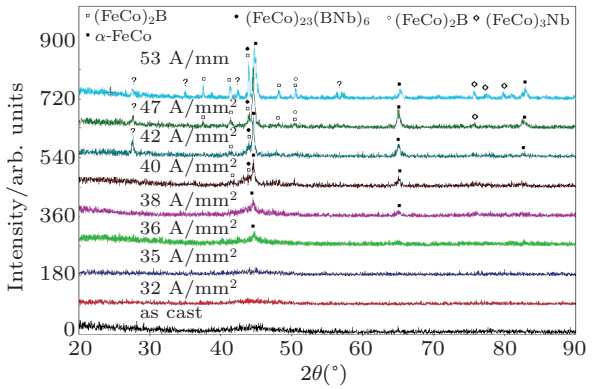



**Fig. 9.** (colour online) The XRD profiles of FeCo-based ribbon annealed with various annealing currents.

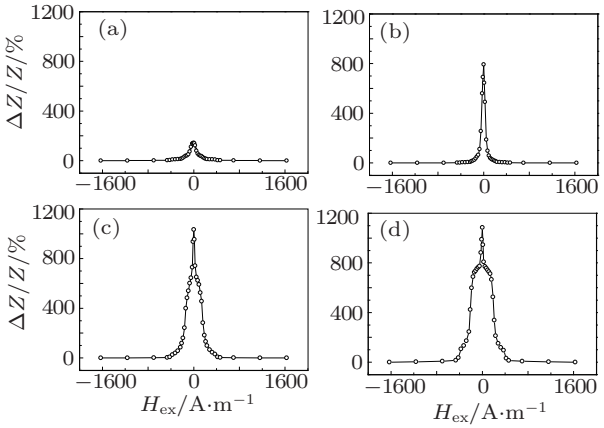



**Fig. 10.** TGMI profiles of MCS containing Joule-heated FeCo-based ribbon corroded to thicknesses of (a) 5 μm, (b) 17 μm, (c) 30 μm, and (d) 45 μm by 16.7% HCl solution.

The TGMI effect may result from the multiple magnetic-anisotropic structure, which is induced by the temperature gradient produced during Joule-heating ribbon. The temperature at the inner shell of the ribbon is higher than at the outer shell during the ribbon being Joule-annealed in flowing nitrogen atmosphere, because the heat from the outer shell is removed more rapidly than that from the inner shell.

## 5. Conclusion

The following conclusions can be drawn from the present study. 1) The TGMI effect has a high magnetic sensitivity under a WMF. The TGMI effect of the MCS containing FeCo-based ribbon relates closely to the annealing current density and the driven current frequency. Here, the TGMI effect appears only in a narrow annealing current density range of 30–34 A/mm$^2$ and a driving current frequency range

of 200–500 kHz. The highest magnetic sensitivity $\xi_{\mathrm{Tmax}} = 1580\ \%/\mathrm{A{\cdot}m^{-1}}$ appears at 350 kHz in the amorphous ribbon annealed at 32 $\mathrm{A/mm^2}$ for 600 s. 2) The multiple magnetic structure of the FeCo-based amorphous ribbon can be controlled by current annealing in flowing nitrogen atmosphere. The TGMI effect can be obtained by this multiple magnetic structure controlling method.

# References


[1] Li Y F, Feng S Q and Wang J Y 2011 *Acta Phys. Sin.* **60** 630 (in Chinese)

[2] Yang J, Wang Z, Jia Y Y and Han Y M 2010 *Acta Phys. Sin.* **59** 8148 (in Chinese)

[3] Pan H L, Cheng J K, Zhao Z J, He J K, Ruan J Z, Yang X L and Yuan W Z 2008 *Acta Phys. Sin.* **57** 3230 (in Chinese)

[4] Bao B H, Ren N F and Luo Y 2011 *Acta Phys. Sin.* **60** 666 (in Chinese)

[5] Xin H L, Yuan W Z, Cheng J K, Lin H, Ruan J Z and Zhao Z J 2007 *Acta Phys. Sin.* **56** 4152 (in Chinese)

[6] Kim C G, Jang K J, Kim Y C and Yoon S S 1999 *J. Appl. Phys.* **85** 5447

[7] Jang K J, Kim C G, Yoon S S and Shin K H 1999 *IEEE Trans. Magn.* **35** 3889

[8] Kim C G, Kim C O and Yoon S S 2002 *J. Magn. Magn. Mater.* **249** 293

[9] Rheem Y W, Jin L, Yoon S S, Kim C G and Kim C O 2003 *IEEE Trans. Magn.* **39** 3100

[10] Rosales-Rivera A, Valencia V H and Pineda-Gómez P 2007 *Physica* B **389** 252

[11] Zhukova V, Ipatov M, Gonzalez J, Blanco J M and Zhukov A 2008 *J. Appl. Phys.* **103** 07E714

[12] Yang J X, Yang X L and Chen G 1998 *Chin. Sci. Bull.* 43 1051 (in Chinese)

[13] Fang Y Z, Zheng J J, Wu F M, Xu Q M, Zhang J Q, Ye H Q, Zheng J L and Li T Y 2010 *Appl. Phys. Lett.* **96** 092508

[14] Li Z W, Yang X, Wang H B, Liu X and Li F S 2009 *Chin. Phys.* B **18** 4829

[15] Ao Q, Zhang W L, Zhang Y and Wu J S 2007 *Acta Phys. Sin.* **56** 1135 (in Chinese)

[16] Buznikov N A, Kim C G, Kim C O and Yoon S S 2004 *Appl. Phys. Lett.* **85** 3507