Influence of the distance between two voltage contacts on giant magneto-impedance of Co-based amorphous wires*

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The $Co_{75}Fe_{4.2}Si_8B_{12}Nb_{0.8}$ amorphous wires of 30 μm in diameter are produced by melt extraction and annealing at 450 °C for 20 min in vacuum with a longitudinal or transverse field of 40 kA/m. Distances between the two voltage contacts of 6, 5, 4 and 2 mm are obtained by moving the two voltage contacts towards the centre of the sample at the same time. Results indicate that magneto-impedance response is dependent on the distance significantly. As distance decreases from 6 to 2 mm, $\Delta Z/Z$ reduces from 609% to 95% and giant magneto-impedance (GMI) profiles change from two-peak to single-peak. Besides, field sensitivity improves from 0.47%/(A/m) to 0.76%/(A/m) when the single-peak GMI just appears. It is therefore concluded that actual measurements can be made comparable only by taking into account the influence of distance between two voltage contacts for a magneto-impedance measurement.

Keywords: GMI effect, amorphous wire, magnetic field anneal, domain structure
PACC: 7580, 7550K, 7280N, 7220M

1. Introduction

The sensitive change in ac impedance of ferromagnetic materials caused by an external dc magnetic field applied is defined as giant magneto-impedance (GMI) effect,[1,2] which depends on the change in sensitivity of circular permeability and skin effect.[1,3,4] It has attracted a lot of attention from the research community in recent years due to its great potential applications in MI sensors and magnetic recording.[2,5−8] The magnetic structure of Co-rich amorphous wires is determined by the magnetoelastic coupling between the local direction of magnetisation in the material and the residual stress induced during solidification, as well as by exchange and magnetostatic effects. These lead to a core–shell magnetic structure:[9−11] A cylindrical inner core axially is enveloped by a circumferential outer shell. And the sample geometry influence on the magnetisation and GMI effect[12−15] has been investigated. For example, Vazquez *et al.*[12] have discovered as the length of a sample or the distance to one end of wires decreases, the increase of border effect reduces the circular permeability and GMI effect. As the sample length decreases, close to the wire ends, the border effect gets strong which induces the magnetisation hardening and a decrease of susceptibility. Therefore, GMI effect decreases and GMI shoulders appear at an increasing dc field H_{ex} as sample length or distance to one end decreases. Furthermore, they found[12] that the field sensitivity was reduced when such a border effect was strong. While, Phan and Peng found[2] the magneto-impedance ratio of Co-based glass-covered wires increased from 15.5% to 268% as the sample length decreased from 4 to 1 mm at 10 MHz. However, the effective sample length is determined by the distance between the two voltage contacts. In order to further study the influence of sample length on GMI effect different distance between voltage contacts is obtained by moving the two voltage poles towards the centre of the wire at the same time, which is different from those used before. And magneto-impedance is measured at different distances. Then the influence of the distance between the two voltage contacts on GMI effect is discussed.

2. Experiments

Amorphous wires of $Co_{75}Fe_{4.2}Si_8B_{12}Nb_{0.8}$ with a diameter of 30 μm are produced by a melt extraction technique[16] in an argon atmosphere. Then the wires are annealed at 450 °C for 20 min under a magnetic field of 40 kA/m in a tubular furnace. When the magnetic field is parallel to the axis of wire, the anneal treatment is called longitudinal field anneal

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(LFA) and when the magnetic field is perpendicular to the axis of wire it is called transverse field anneal (TFA). The wires are characterised by x-ray diffraction (XRD) with a monochromatized Cu Kα radiation. Actual measurements indicate they are still of amorphous structure after annealing. Two pieces of TFA and LFA wires of 30 mm in length are connected with Ag paint using a four point's technique in the measuring electro-circuits. Different measuring distances between contacts of 6, 5, 4 and 2 mm are obtained by moving the two voltage poles towards the wire centre at the same time. Giant magneto-impedance is measured at room temperature of about 25 °C. Impedance Z is measured with Agilent 4294 impedance analyzer. External dc axial magnetic field $H_{\rm ex}$ is supplied by a pair of Helmholtz coils and the maximum field intensity is 8 kA/m. The ac current is steady at 20 mA and the ac current frequency ranges from 1 to 110 MHz. The dc field is kept perpendicular to the earth magnetic field to diminish the influence of the earth.

Impedance ratio can be defined as

$$\Delta Z/Z(\%) = [Z(H_{\rm ex}) - Z(H_{\rm max})]/Z(H_{\rm max}) \times 100\%,$$

where $Z(H_{\rm ex})$ and $Z(H_{\rm max})$ are the impedance values when the external magnetic fields are $H_{\rm ex}$ and the maximum magnetic field of 8000 A/m, respectively. Maximum GMI ratio $\Delta Z/Z(\%)$ is called $\Delta Z/Z(\%)$ m. The corresponding GMI field sensitivity is defined as $Q = {\rm d}(\Delta Z/Z(\%))/{\rm d}H$. Maximum field sensitivity Q is called $Q_{\rm m}$.

3. Result and discussion

The GMI response of annealed wires is measured at lower and middle frequencies at different distances. Figure 1 shows the GMI feature of a piece of TFA wire as a function of external field $H_{\rm ex}$ at 10 MHz. Giant magneto-impedance ratio $\Delta Z/Z(\%)$ decreases as external field $H_{\rm ex}$ increases, and maximum values $\Delta Z/Z(\%)_{\rm m}$ appear at $H_{\rm ex} = 0$ A/m, exhibiting typical single-peak behaviours at this frequency. The maximum impedance ratio $\Delta Z/Z(\%)_{\rm m}$ reduces from 115% to 14.5% as the distance decreases from 6 to 2 mm. These results indicate that the impedance response is influenced by the distance between the two voltage contacts. It is found that GMI profiles are single-peaked at a frequency below 15 MHz. Two-peak GMI curves appear at higher frequencies[17] because the wall displacement is damped by eddy current, and the rotation magnetisation gradually dominates the circular permeability. $\Delta Z/Z(\%)$ increases as the external field $H_{\rm ex}$ increases, and reaches the peak value when $H_{\rm ex}$ is equivalent to the effective circular anisotropy field $H_{\rm m}$. Then two peaks appear at $\pm H_{\rm m}$.[1] The effective circular anisotropy field is correlated with the circular anisotropy field and the coercivity, which in turn reflects the anisotropy field.

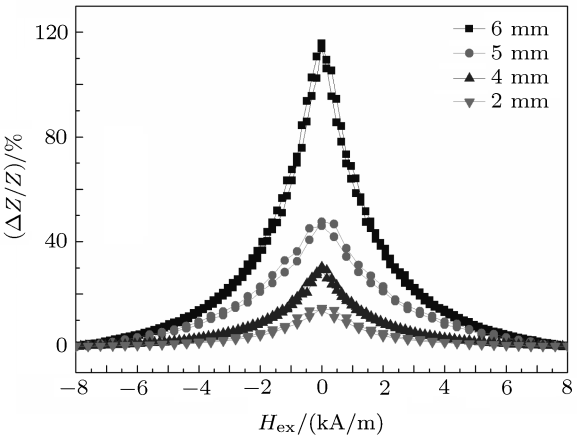


Fig. 1. GMI curves of TFA wires for different distances between the contacts at 10 MHz.

At higher frequencies the distance dependence is much more distinct. GMI curves of these two field-annealed wires at 37 MHz are shown in Fig. 2. At distance of 6 mm, $\Delta Z/Z(\%)$ increases gradually and then reaches the peak at $\pm H_{\rm m}$ as $H_{\rm ex}$ increases, showing two-peak GMI. While GMI curves of TFA wires change to single-peak when distance decreases to 2 mm as shown in Fig. 2(a). And $\Delta Z/Z(\%)_{\rm m}$ decreases from 609% to 95% as the distance decreases from 6 to 2 mm. The corresponding effective circular anisotropy fields are 2.32 kA/m, 1.92 kA/m and 0.8 kA/m respectively at distances of 6, 5 and 4 mm, indicating a decrease of circular anisotropy field. It is investigated that the local domain structures are different at different positions of these Co-based amorphous wires.[18] The border effect gets stronger as the two voltage contacts moving towards the ends[18] at the same time, due to the twisted magnetisation of the inner core at the ends of Co-based amorphous wires. And the circular anisotropy field is increased at the ends of these Co-based wires. Due to this fact, the circular anisotropy field is reduced as the distance decreases. Hence the circular permeability and GMI response decrease as the distance decreases. When the distance decreases to 2 mm, the border effect is weak and the circular anisotropy field is small, thus the circular permeability reduces as the external field increases. The largest value of impedance ratio appears at small effective circular anisotropy field which is almost zero. Consequently, single-peak GMI curves are observed.

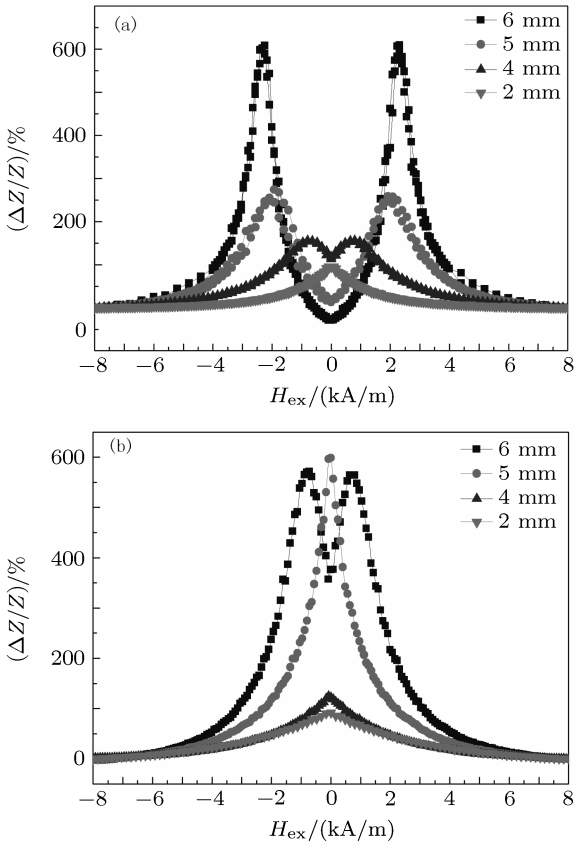


Fig. 2. GMI curves of TFA wire (a) and LFA wire (b) at 37 MHz for different distances between the contacts.

This significant influence of distance on GMI response is also observed in LFA wires, as shown in Fig. 2(b). Values of $\Delta Z/Z(\%)_{\rm m}$ are 571%, 598.8%, 122% and 91.3% for distances of 6, 5, 4 and 2 mm, respectively. When the distance is 5 mm, GMI curves change into single-peak. Effective anisotropy field $H_{\rm m}$ for distance of 6 mm is 0.72 kA/m only, which is much smaller than that in TFA wires, implying less circular anisotropy field. The magneto-impedance response is stronger and the circular anisotropy field is larger in TFA wires than those in LFA wires at the same distance, indicating that different domain structures are induced by field annealing. These Co-based amorphous wires have 'core-shell' model domain structures.[11,19] There are axial domains in the core surrounded by circular domains in the outer shell. The transverse field can modify the circular domain structures.[20] Due to this fact, at the same distance, the circular anisotropy field is much smaller in LFA wires, inducing worse GMI response and less effective circular anisotropy field. It is also found that the permeability properties and electromagnetic properties of Fe-based extraction wires are clearly affected by anneal treatment.[21,22] The improved circular anisotropy field leads to a larger saturation field, too. Consequently, in TFA wires, the impedance Z at a field $H_{\rm ex} = 8$ kA/m is much larger than the corresponding value at saturation field, and it is also larger than the impedance at $H_{\rm ex} = 0$ kA/m. Then the impedance ratio of $\Delta Z/Z(\%)$ is negative at near zero field for the TFA wire, as shown in Fig. 2(a).

These different features of GMI response between field-annealed wires permit us to believe that different magnetic field anneal treatments induce the change of permeability and GMI response. The single-peak and two-peak different behaviours as functions of distance between contacts for wires should be related to the circular domain structures. Just at the middle of the wire, border effect is weak and there is a nearly axial magnetisation domain inducing single-peak GMI curves. While for larger distances, the border effect induces a larger circular anisotropy field and hence two-peak GMI curves. Then we can draw a conclusion that magneto-impedance is dependent on the position of contacts as a consequence of the susceptibility profile and the local domain structures determined by the finite distance between the two voltage contacts.

In addition, the decrease of effective circular field results in an increase in field sensitivity. Field sensitivity $Q_{\rm m}$ is 0.08%/(A/m) only with impedance ratio of 155% in TFA wires at a distance between contacts of 4 mm. Then field sensitivity $Q_{\rm m}$ goes up to 0.09%/(A/m) with good linearity when single-peak curve appears at distance of 2 mm. When single-peak curve is present at 5 mm in LFA wires, the field sensitivity $Q_{\rm m}$ increases from 0.47%/(A/m) to 0.76%/(A/m).

4. Conclusion

In conclusion, actual measurement analysis indicates that the sample length determined by the distance between the two voltage contacts has a significant influence on the GMI response. When the distance is short, GMI is single-peak and typically of small amplitude. For longer distances GMI becomes two-peak and typically of larger amplitude. These results are the consequence of the difference of local domain structures. For short distances, at the middle of the wire, single axial domain structure with small circular susceptibility is present. As distances increase, the contacts are close to the wire ends and the border effect gets stronger, which contributes to a larger circular anisotropy field and hence two-peak GMI effect.

It is therefore concluded that the magneto-impedance data can be made comparable only by taking into account the influence of distance between two voltage contacts.

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