Wire-length effect on GMI in Co$_{70.3}$Fe$_{3.7}$B$_{10}$Si$_{13}$Cr$_3$ amorphous glass-coated microwires

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1. Introduction

The discovery of giant magnetoimpedance (GMI) effect in soft ferromagnetic amorphous microwires makes them a very attractive candidate material for making high-performance magnetic sensors [1–6]. The use of such microwires could also have implications for the next generation of electronic devices, which will involve increasingly smaller components [7–9]. GMI is termed as the giant variation of impedance of a ferromagnetic conductor with an ac current in an applied dc magnetic field [10]. The origin of GMI is related to the classical skin effect, which refers to the fact that an applied ac current of high frequency concentrates mainly on the outer part of the magnetic material. It is parameterized by the skin depth $\delta$, which, in the case of a magnetic wire, can be calculated by [10]:

$$\delta = \frac{c\sqrt{\rho}}{2\pi \sqrt{f\mu_p}}.$$  (1)

where $\rho$ is the electrical resistivity, $f$ is the frequency of a driving ac current and $\mu_p$ is the circumferential permeability. Accordingly, the impedance of the wire ($Z$) can be calculated by [11]:

$$Z = 2R_0 k a J_0(ka)$$  (2)

where $R_0$ is the dc electrical resistance, $J_0$ and $J_1$ are the Bessel functions of the first kind, $a$ is the wire radius and $k=(1+j)/\delta$ with $j$ as the imaginary unit. It follows that a large GMI effect should be achieved in wires with large $\mu_p$, small $\rho$ and $\delta$. Since these parameters depend strongly on microwire geometry (e.g., the length, diameter, and aspect ratio of the microwire), varying the geometrical dimensions of a microwire can significantly modify its magnetic properties and hence GMI behavior. While a clear understanding of the influence of wire geometry on GMI effect is essential for design and fabrication of highly sensitive GMI-based sensors, only a few studies have been reported in the literature [12–21]. Vazquez et al. [13] investigated the influence of the sample length on the magnetic properties and GMI effect in Fe-based nanocrystalline wires. They showed that with decreasing wire length from 8 to 1 cm, the coercivity increased, the susceptibility decreased, and the GMI effect consequently reduced. However, Phan et al. [14] observed that the GMI effect increased in Co-based amorphous microwires as the microwire length decreased from 4 to 1 mm. This contrast suggests two different mechanisms that governed the observed GMI effects. Zhukova et al. [15] have demonstrated that there exists a critical length of the wire below which the spontaneous magnetic bistability of a Co-based amorphous wire is lost. The loss of magnetic bistability was attributed to the influence of shape anisotropy, where, for short wires, the demagnetizing field became large enough to destroy the original domain structure of the sample [8]. Accordingly, it is thought that, in the case of Fe-based nanocrystalline wires [16], the critical length could be larger than 8 cm and therefore, with decreasing wire length, the demagnetization effect was strong enough to destroy the original domain structure of the wire (e.g., the formation of closure domain structures due to the demagnetization effect) leading to the decrease of GMI effect. In the case of Co-based microwires [14], however, the
critical length of the microwire could be smaller than 1 mm, and the increase of GMI effect was attributed to the decrease of electrical resistance. Nevertheless, an in-depth understanding of the influence of wire geometry on GMI profiles is needed.

In the present study, the wire-length effect on GMI in Co$_{70.3}$Fe$_{3.7}$B$_{10}$Si$_{13}$Cr$_3$ amorphous glass-coated microwires was investigated. The results obtained reveal that there exists a critical length of the microwire, below which the GMI effect is in favor of shorter length and above which longer microwires present a more sensitive dependence of the real component of the impedance to the frequency variation. The simplified skin-effect model has been found to well explain the observed GMI behaviors.

2. Experimental

Soft magnetic amorphous glass-coated microwires of Co$_{70.3}$Fe$_{3.7}$B$_{10}$Si$_{13}$Cr$_3$ have been fabricated by a modified Taylor–Ulitovski method [22–24]. These microwires consist of the metallic core of 29.2μm in diameter and the glass cover of 7.5μm thick. The lengths of the microwires measured were $l = 5, 10$, and $15$ mm. The microwires possess good soft magnetic properties owing to their vanishing magnetostriction ($\sim 10^{-7}$) and are suitable for the MHz operation [25,26]. The magnetoimpedance was measured by a HP8753E network analyzer in the frequency range of 1–10 MHz. The wire samples were set in the measuring cell subjected to the dc magnetic field of up to 30 Oe along the wire axis and vertical to the geomagnetic field. S11 port of the two-port network was applied to pick up the signal of output power and the S-parameter was then converted to the impedance by program calculation. The magnetoimpedance ratio $\Delta Z/Z$ is defined as

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

where $Z(H)$ and $Z(H_{\text{max}})$ is the impedance values of the samples in the arbitrary magnetic field and the maximum magnetic field to saturate the impedance, respectively.

3. Results and discussion

Fig. 1 shows the magnetic field dependence of magnetoimpedance ratio (MIR) at different frequencies $f = 1$, 2, 4, and 10 MHz for microwires with $l = 5, 10$ and $15$ mm. It can be seen in Fig. 1(a) that at $f = 1$ MHz the MIR of the 15 mm microwire almost has no response to an external magnetic field. Meanwhile, the 5 and 10 mm microwires exhibit the GMI effects and a single-peak feature is observed in the GMI curves for these samples. As the
frequency is increased (f = 2 MHz), however, all the three samples show the GMI effects (see Fig. 1(b) and its inset). The GMI curves exhibit a single-peak feature for the 15 mm microwire but a double-peak feature for the 5 and 10 mm microwires. At higher frequencies (f = 4 and 10 MHz), the double-peak feature is observed for all the samples (Fig. 1(c) and its inset) and becomes more pronounced for f = 10 MHz (Fig. 1(d) and its inset). It is worth mentioning that for all the microwires, the magnitude of MIR increases with increasing frequency and decreasing microwire length. More noticeably, at the highest measured frequency (f = 10 MHz), the magnitude of MIR is larger for the 15 mm microwire than for the 10 mm microwire. This intriguing feature is further elucidated by the frequency dependence of maximum MIR as shown in Fig. 2.

This finding can be explained by considering the relative contributions of μ₀ and f to δ and hence to GMI effect [10]. We first recall that application of a dc magnetic field along the microwire would suppress the circumferential permeability, which in turn results in an increase of skin depth and consequently yields the large variation of the impedance. Since longer microwires tend to have less influence on the magnetic flux on the longitudinal direction, in analogy to the decrease of the cross-sectional area of the microwire, the permeability is decreased to a lesser extent, which gives a possible larger skin depth. On the other hand, the increase of frequency results in an opposite effect (i.e. the skin depth decreases with increasing frequency). This thus leads to a general expectation that there exists a critical length effect in a certain frequency range.

As the wire length is smaller than the critical length, the GMI effect increases with decreasing wire length. However, when the wire length is larger than the critical length, longer wires possess a more sensitive dependence to higher frequency thus resulting in larger values of GMI in these wires. Putting our results in this perspective, it appears that the critical length of a Co70.3Fe3.7B10Si13Cr3 microwire lies between 10 and 15 mm in the frequency range of 1–10 MHz (see Fig. 2). Since the skin depth essentially determines the penetration depth using the simplified skin-effect model developed by Knobel et al. [27,28]. This model is based on the assumption that the variation of the effective area where the ac current concentrates governs the change of the real component of the impedance. When the wire radius is larger than the skin depth (a > δ), the skin depth is calculated by

\[ \delta = a \left(1 - \sqrt{1 - \frac{R_{dc}}{R_{ac}}}\right), \]  

where \( R_{dc}/R_{ac} \) is the ratio between the dc resistance and the real component of impedance, which is determined by GMI measurements.

Fig. 3 illustrates the magnetic field dependence of multiplicative inverse of \( \delta \) at f = 4 and 10 MHz. The shapes of the calculated curves are in good agreement with those of the corresponding experimental curves. Since \( Z \propto \delta^{-1} \), it appears that the GMI behavior of the wires with varied length in the frequency range of 1–10 MHz is well explained by this model. We note that for the case of the 15 mm microwire, the graph of the calculated \( \delta \) is partially missing because \( a < \delta \), or \( R_{ac} < R_{dc} \), which is unphysical and indicates the inapplicability of Eq. (4) in this condition.

Fig. 4 shows the magnetic field dependence of the real part of the impedance (\( R_{ac} \)) at 4 and 8 MHz for the 10 and 15 mm microwires. It can be seen that \( R_{ac} \) is proportional to the wire length for both frequencies, and it increases strongly with frequency for both the 10 and 15 mm microwires. We denote \( R_{ac1} \) and \( R_{ac2} \) as the real component of maximum impedance for the 10 and 15 mm microwires, respectively. With the aid of the model, the comparison between GMI values for these microwires is equivalent to that of the \( R_{dc} \) to

\[
\frac{\text{GMI}_{\text{max}2} - \text{GMI}_{\text{max}1}}{\text{GMI}_{\text{max}2}} \propto \frac{R_{dc1} - R_{dc2}}{R_{ac1} - R_{ac2}} \propto \frac{R_{ac1} \times R_{ac2}}{R_{dc1} \times R_{dc2}}
\]

As \( R_{dc1} = 28 \, \Omega, R_{dc2} = 48 \, \Omega \), the variation of GMI can be written as

\[
\Delta \text{GMI} \propto 28R_{ac2} - 48R_{ac1}
\]
The GMI effect in Co_{70.3}Fe_{3.7}B_{10}Si_{13}Cr_{3} amorphous glass-coated microwires with varying wire length has been investigated experimentally and theoretically in the frequency range of 1–10 MHz. We show that there exists a critical length effect, which distinguishes the different wire-length dependencies of GMI. Below the critical length, the GMI effect is in favor of shorter length. Above the critical length, longer microwires possess a more sensitive dependence of the real component of the impedance to the frequency variation. The calculated results using the simplified skin-effect model support these findings.

4. Conclusions

The GMI effect in Co_{70.3}Fe_{3.7}B_{10}Si_{13}Cr_{3} amorphous glass-coated microwires with varying wire length has been investigated experimentally and theoretically in the frequency range of 1–10 MHz. We show that there exists a critical length effect, which distinguishes the different wire-length dependencies of GMI. Below the critical length, the GMI effect is in favor of shorter length. Above the critical length, longer microwires possess a more sensitive dependence of the real component of the impedance to the frequency variation. The calculated results using the simplified skin-effect model support these findings.

Acknowledgements

FXQ is the recipient of the Overseas Research Students Awards Scheme and the University of the Bristol Postgraduate Student Scholarship. HXP would like to acknowledge the financial support from the Engineering and Physical Science Research Council (EPSRC) UK under the Grant No. EP/F03850X. The authors would also like to thank Prof. Larissa V. Panina and Nick Fry for their help with GMI measurements.

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