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High-frequency magnetoimpedance effect in glass-coated amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwires

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Measurements of the giant magnetoimpedance (GMI) were carried out in the amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ micro-wires at high frequency range from 100 MHz up to 1 GHz of an ac-current flowing along the wire and at varying axial dc-magnetic field in its range of ±120 Oe. The wires, about 15 μm in diameter, were fabricated by a glass-coated melt spinning technique. The shapes of the impedance curves plotted vs. a dc-field change dramatically with the frequency. The phase angle was also strongly dependent on the field. The maximum value of GMI, around 250%, was reached at the frequency of about 500 MHz. The external dc-magnetic field changes the circumferential permeability as well as the penetration depth, both in turn change the impedance of the sample. The increments of GMI at high frequency can be understood in terms of the LC-resonance phenomena. A sudden change of the phase angle, as large as 180°, evidenced the occurrence of the resonance at a given intensity of the external dc-field.

Key words: magnetoimpedance effect; microwires; magnetic sensors

1. Introduction

Giant magnetoimpedance (GMI) effect has been intensively studied because of the increasing prospects of novel applications in magnetic sensors [1]. The phenomenon has a classical electromagnetic origin and is due to a simultaneous occurrence of the skin effect and the changes of the transverse or circumferential permeability under the influence of an external dc-magnetic field applied along a magnetic element [2]. As a consequence, the impedance of a wire, $Z = R + iX$, is altered by the external axial magnetic field (both its components, the resistance R and the reactance X vary with this field). A majority of studies carried out so far have mainly been devoted to investigations of the mechanisms of these complex phenomena at relatively low frequency (radio frequency range) of the ac-current flowing through the sample in the form of a thin ribbon or wires. However, it has been shown that this effect is of very large

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magnitude in tiny magnetic wires of a micrometer-diameter. The behaviour of the GMI effect at very high frequencies has not been hitherto studied intensively in spite of their importance from the view-point of both, basic knowledge and technological applications. High-frequency sources are nowadays easily available in communication electronics such as PCs, cellular phones, GPS, etc. It might be expected that the GMI sensors operated at such high frequencies could well be adapted to these electronics, being profitable since at high frequencies the penetration depth is very small.

For a cylindrical magnetic conductor, its impedance can be expressed as

$$Z = R_{dc} ka \frac{J_0(ka)}{2J_1(ka)} \tag{1}$$

where R_{dc} is the dc-resistance of the wire, J_0, and J_1 are the Bessel functions of the first kind, $k = (1 + i)/\delta$, where δ is the penetration depth $\delta = c/(2\pi\omega\sigma\mu_\phi)^{1/2}$, a – the radius of the wire, ω – the angular frequency, σ – the conductivity of the wire, and μ_ϕ – the effective complex magnetic permeability in the circumferential direction [3]. At high frequency range within which $\delta << a$, the changes of the impedance are roughly proportional to $Z \propto (\omega\mu_\phi)^{1/2}$ [4, 5]. Therefore, in this frequency range, the total impedance of a magnetic wire is proportional to the square root of the circumferential permeability μ_ϕ.

To achieve large GMI, the penetration depth should be very small in the absence of an external magnetic field. Large circumferential permeability along with a low value of the resistivity gives rise to a small penetration depth at a high frequency range. A large increase of the circumferential permeability can be achieved applying an ac-current of the frequency sufficiently high to excite the resonance of the sample, which constitutes a LC-resonator at this frequency range. This large circumferential permeability strongly decreases the penetration depth and, therefore increases the impedance of the sample.

Since the circumferential permeability equals

$$\mu = 1 + 4\pi\chi(\omega, H)$$

the inductance L of a microwire becomes

$$L = L_0\big(1 + 4\pi\chi(\omega, H)\big),$$

where

$$\chi = \chi'(\omega, H) - i\chi''(\omega, H)$$

is a complex susceptibility dependent on ω and H. Therefore, the impedance Z of a microwire in the vicinity of the resonance becomes

$$Z = iL_0\omega(1 + 4\pi\chi') + L_0\omega 4\pi\chi'' + R_0$$

Recently developed amorphous microwires were found to be more promising for several applications compared to amorphous thicker wires and ribbons because of their tiny dimensions, superior magnetic properties and a protective glass coating. In this study, we have investigated the high-frequency GMI effect in the glass-coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwires.

2. Experimental

Glass-coated amorphous microwires of nominal composition $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ were fabricated using the Taylor–Ulitosky method. The diameter of the metallic core of the sample, measured under an optical microscope, was about 16 μm and the thickness of the insulating glass coating was equal to ~5 μm.

The samples were annealed for 1 hour in vacuum at various temperatures in the range of 150–250 °C in order to settle optimum annealing conditions to achieve the best magnetic softness by reducing residual internal stresses (stress relaxation).

All the measurements of GMI were carried out at a room temperature. A network analyzer (Agilent, 8712ET, 0.3 MHz–1.3 GHz) and an impedance analyzer (HP4191A, 1 MHz–1 GHz), both connected to a computer data acquisition system, were used for these measurements. The power level of the impedance analyzer for the MI measurement was fixed at –20 dBm. A dc-magnetic field, applied in an axial direction, was swept through the entire cycle between –120 Oe and 120 Oe.

The ratio of the magnetoimpedance (MIR), dependent on the external magnetic dc-field, is usually expressed as

$$MIR\,(\%) = \frac{\Delta Z}{Z}(\%) = 100\times\left[\frac{Z(H)-Z(H_{\max})}{Z(H_{\max})}\right] \tag{2}$$

where $H_{\max}$ is the maximum intensity of the dc-field applied (in the present experiment $H_{\max}$ = 120 Oe). Equation (2) was applied to calculate the magnetoimpedance ratio MIR using the data obtained in the experiment.

3. Results and discussion

It was found that the sample annealed at 180 °C displayed the best magnetic softness, hence this wire-specimen was used in the experiment.

Figure 1 shows the MIR curves calculated using the experimental data obtained at different frequencies and plotted as a function of the external axial dc-field. As is seen in the figure, the maximum value of MIR increases drastically with an increase of the frequency up to 550 MHz. This is mainly due to a decrease of the penetration depth, whose value is estimated smaller than 1 μm at the frequencies used in the experiment.

The dominating contribution to the effective permeability comes either from the rotation of magnetization or from the domain wall motion [6]. In general, depending on the frequency, three main mechanisms of the GMI-effect can be distinguished, namely: (i) at relatively low frequencies the changes of the impedance are entirely ascribed to the magnetoinductive effect arising from the circular magnetization processes, (ii) at high frequencies, the skin effect becomes dominant because of the large permeability, and (iii) at very high frequencies, a motion of domain walls is totally damped and the permeability rapidly decreases until the resonance phenomena are reached [7].

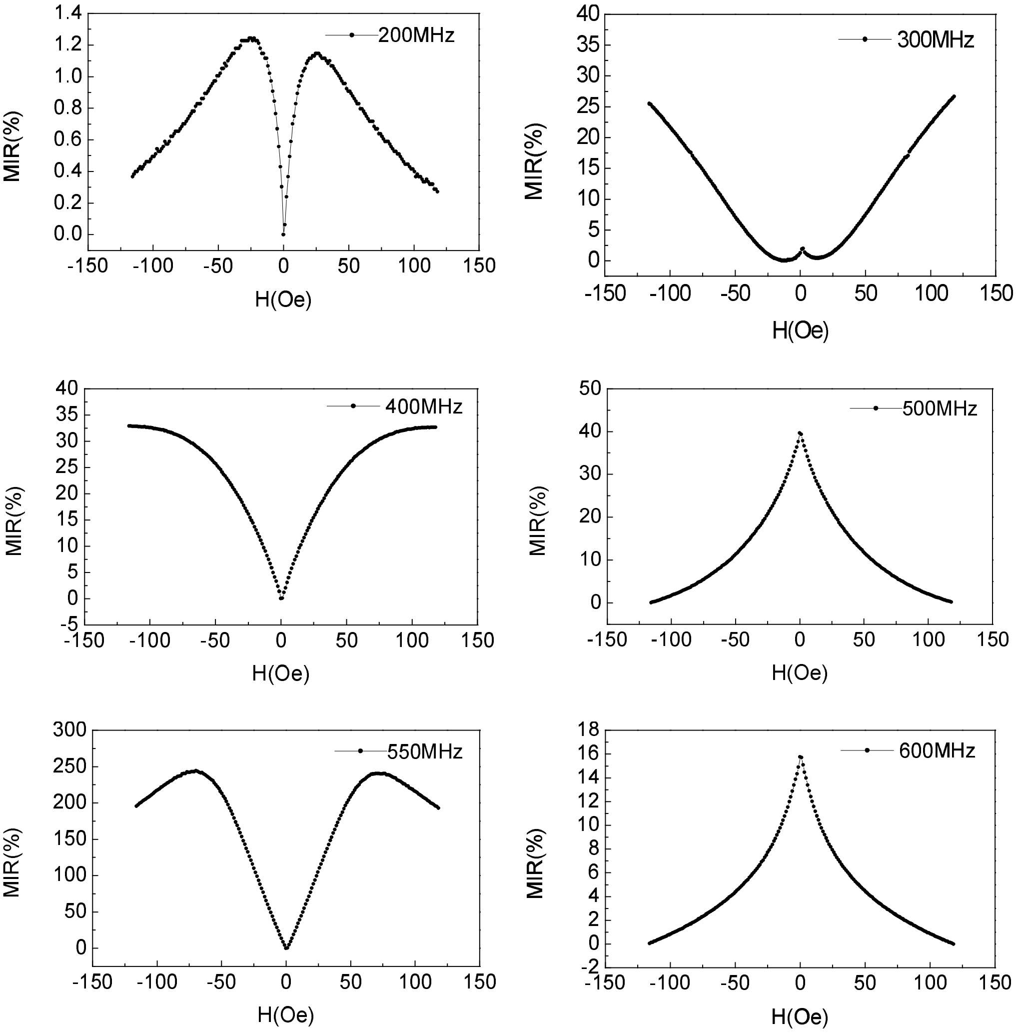

Fig. 1. MIR curves measured at various frequencies (200, 300, 400, 500, 550, 600 MHz)

Because the frequencies of the ac-current flowing along the wire-sample are very high, the obtained experimental dependencies of GMI can be interpreted in accordance with the case (iii), where the domain walls are immovable. Therefore, the MIR curve obtained at 200 MHz can be understood considering the above case. At the frequencies above

200 MHz, a dramatic increase of the MIR value is observed, due to the occurrence of the resonance. At very high frequency range, the sample behaves like a RLC-electric circuit, where R is its resistance, L – the inductance and C – capacitance. Therefore, the resonance frequency of the sample can be given by the well-known expression

$$\omega_r(\omega, H) = \frac{1}{\sqrt{L(\omega, H)C}} \tag{3}$$

where ω is the angular frequency of the ac-current flowing along the wire-sample.

Since the inductance $L(\omega, H)$ depends on the external dc-field as well as on the frequency, the resonance frequency of the sample depends also on these quantities. This is reflected by the complex shapes of the MIR-curves shown in Fig. 1.

In order to simulate the GMI behaviour based on the concept of a LC-resonator, it can roughly be assumed that the inductance L does not depend on the frequency in its range used in the experiment. It can be expressed as

$$L(H) = L_0\left(1 - \alpha H^{0.5}\right)$$

where L_0 is the inductance at $H = 0$, and α is a constant. The inductance simulated in such a way is shown in Fig. 2 as a function of the dc-field.

The impedance and the phase angle can be given by

$$Z(\omega, H) = \sqrt{R^2 + \left(\omega L(H) - \frac{1}{\omega C}\right)^2} \tag{4a}$$

$$\theta(\omega, H) = \tan^{-1}\left(\frac{\omega R}{\frac{1}{C} - L(H)\omega^2}\right) \tag{4b}$$

The impedancies $Z(\omega, H)$ calculated according to Eq. (4a) and plotted as a function of frequency at various intensities of the external dc-field are shown in Fig. 3, where C is taken as 1000 pF estimated from cylindrical condensers of electric terminals at the ends of a microwire. As can be expected, the impedance at frequencies higher than the resonance frequency, $\omega >> \omega_r$, decreases with an increase of the external magnetic dc-field. In the frequency range lower than that of the resonance, $\omega << \omega_r$, an opposite effect is observed, the magnetoimpedance increases with the increase of the external magnetic dc-field.

The calculated impedance curves plotted as a function of the dc-field at different 3 frequencies are shown in Fig. 4. As can easily be noticed, the shapes of these simulated magnetoimpedance curves are much the same as the shapes of those obtained experimentally (see Fig. 1). Similarly, the calculated field dependence of the phase angle (Eq. (4b)), shown in Fig. 5, resembles the experimental one obtained at

550 MHz (close to the resonance frequency). The sudden change of the phase angle as large as 180° gives evidence that the resonance in fact occurs at a specific intensity of the dc-field.

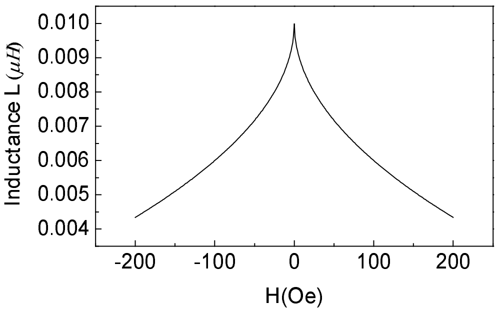

Fig. 2. Calculated inductance L as a function of the external field H

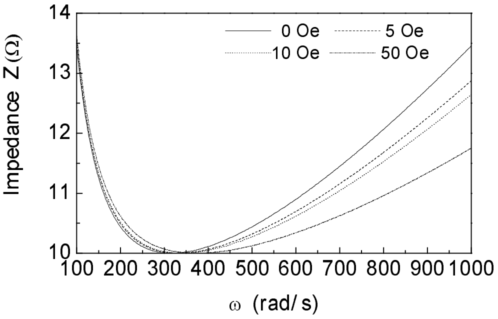

Fig. 3. Calculated impedances Z as a function of frequency ω at various external fields, H = 0, 5, 10, 50 Oe

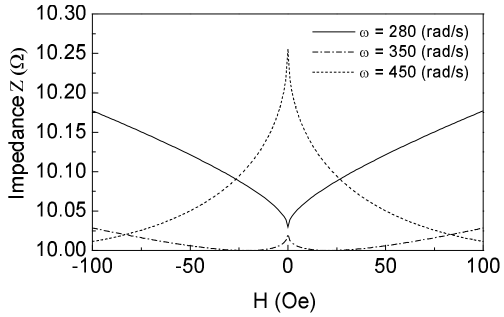

Fig. 4. Calculated impedances Z at different frequencies, ω = 450, 350, 280 (rad/s)

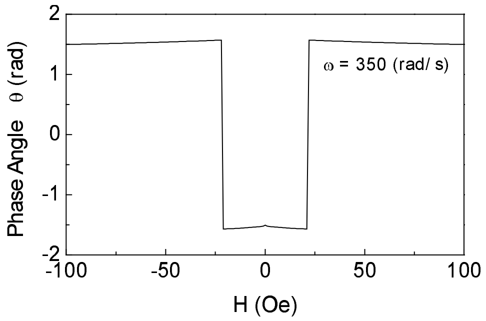

Fig. 5. Calculated phase-angle θ curve at a resonance frequency ω of 350 (rad/s)

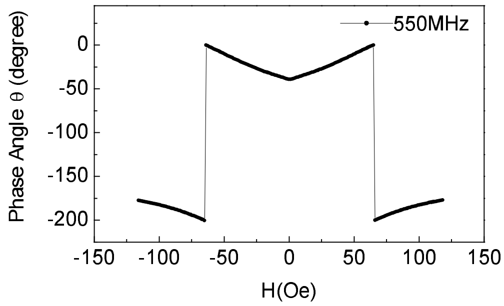

Fig. 6. Phase-angle curve measured at 550 MHz

However, a drastic increase of the ac-current takes place at the resonance frequency. This effect was not taken into account in the performed calculation of the impedance. The large current generates a large circumferential magnetic ac-field in the wire-sample resulting in an increment of the circumferential permeability μ_ϕ. Therefore, a drastic rise of the magnetoimpedance in the vicinity of the resonance frequency can be expected. This is clearly visible in the MIR curve measured at 550 MHz (see Fig. 1).

4. Conclusions

In this study, the giant magnetoimpedance (GMI) effect was investigated in amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire in a very high frequency range up to 1 GHz. The shapes of the dc-field dependencies of the impedance changed dramatically with an increase of the frequency of the ac-current flowing along the sample. The observed increments of the maximum of the magnetoimpedance ratio (MIR) with an increase of the frequency can be interpreted in terms of the LC-resonance phenomena. The maximum value of MIR reached in the experiment equals 250% at the frequency of around 550 MHz. The sudden change of the phase angle, as large as 180°, proved the occurrence of the resonance at the specified intensity of the external dc-field.

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