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Super-giant Magneto-Impedance Effect of a *LC*-resonator Using a Glass-Coated Amorphous Microwire

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A new discovery of the super-giant magneto-impedance (SGMI) effect was found out in a *LC*-resonator consisted of a glass-coated amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire. The measurement was carried out 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 16 μm in diameter, were fabricated by a glass-coated melt spinning technique. The shape of the impedance curves plotted vs. a dc-field is changing dramatically with the frequency. The phase angle was also strongly dependent on this field. 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 drastic increments of SGMI at high frequency can be understood in terms of the *LC*-resonance phenomena. The 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. The maximum ratio of SGMI reached in the experiment by precise tuning frequency equals 450,000% at the frequency of around 551.9075 MHz.

1. Introduction

Giant magnetoimpedance (GMI) effect has intensively been 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 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 magnitude in tiny magnetic wires of a micrometer-diameter. The behaviors of the GMI effect at very high frequencies have not hitherto been studied intensively in spite of their importance from the viewpoint of both, basic knowledge and technological applications. The high frequency sources are easily available nowadays in communication electronics such as PCs, cellular phones, GPS, etc., and 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 $\delta << a$, 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

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*Corresponding author: Tel: +82-41-850-8276, Fax: +82-41-850-8271, E-mail: heebok@kongju.ac.kr 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 high frequency range. A large increase of the circumferential permeability can be achieved applying an ac-current of the frequency sufficiently high to excite a 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 inductanceof a microwire becomes $L = L_C(1 + 5\pi\chi(\omega, H))$, 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 super-GMI (SGMI) effect at near the resonance frequency in a *LC*-resonator consisted of a glass-coated amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire. This is a new discovery of the super-giant magneto-impedance (SGMI) effect in soft magnetic materials.

2. Experiment

Glass coated amorphous microwires of nominal composition $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ were fabricated using Taylor-Ulitosky method. The diameter of the metallic core of the sample, measured in 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 the optimum annealing conditions to achieve the best magnetic softness by reducing residual internal stress relaxation.

The *LC* resonator was consisted of the microwire and two cylindrical electrodes at the end of the microwire

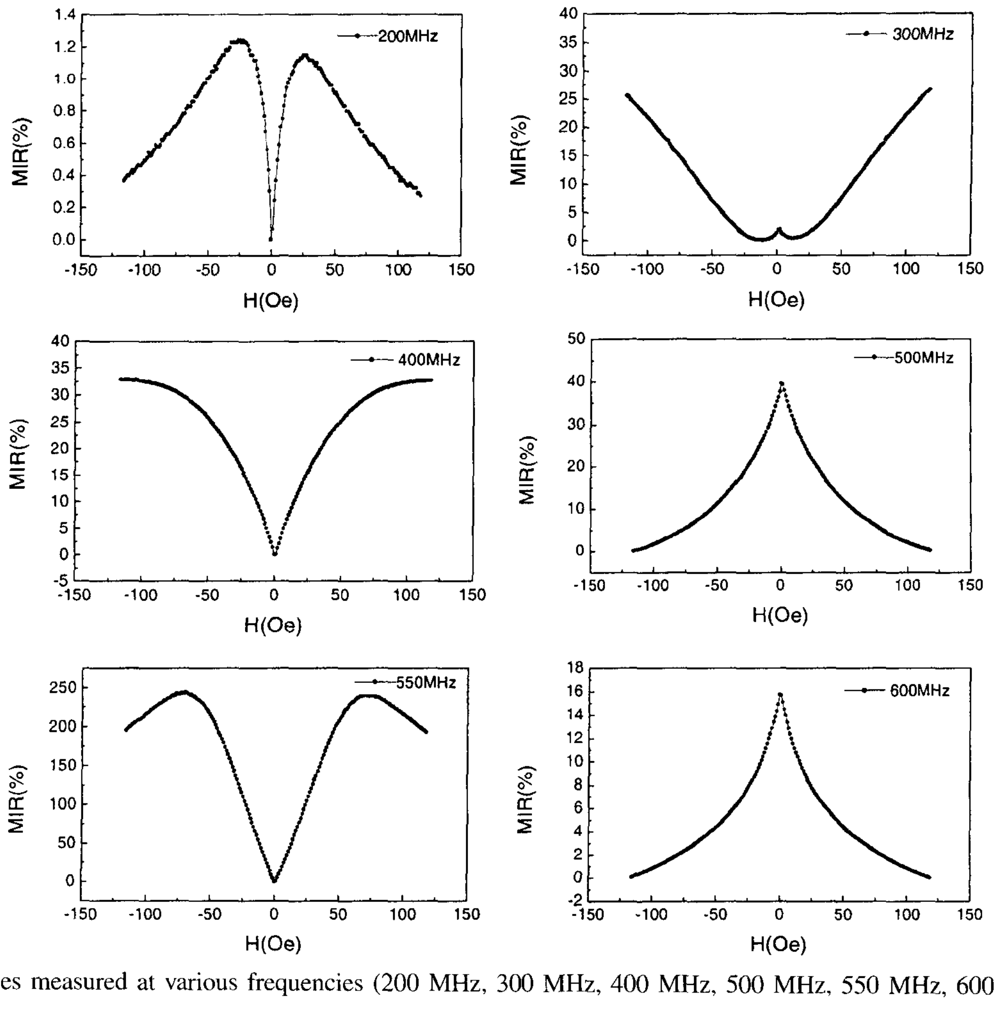

Fig. 1. MIR curves measured at various frequencies (200 MHz, 300 MHz, 400 MHz, 500 MHz, 550 MHz, 600 MHz).

without direct contact to its ferromagnetic core. The length of wire was about 15 mm and the width of electrode was 2 mm, respectively. The electrodes play a role of capacitors in the *LC*-resonance circuit as shown in Fig. 1.

All the measurements of GMI were carried out at 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 controlled data acquisition system, were used for these measurements. 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

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

where $H_{\max}$ is the maximum intensity of the applied dc-field (in the present experiment $H_{\max} = 120$ Oe). Eq. (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 best magnetic softness and, therefore this wire-specimen was used in the experiment.

Fig. 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 it is seen in this 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, the value of which is, at the frequencies used in the experiment, smaller than 1 μm as estimated.

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 magneto-inductive 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]. 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, being 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

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

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 behavior 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 and can be expressed as $L(H) = L_0(1 - \alpha H^{0.5})$, where L_0 is the inductance at $H = 0$, and α is a constant. The inductance simulated this way is shown in Fig. 2 as a function of the dc-field where L_0 is taken as 0.01 μH and α as 0.04 for the numerical calculation, respectively.

The impedance and the phase angle can be given by

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

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

The calculated impedances, $Z(\omega, H)$, according to Eq.

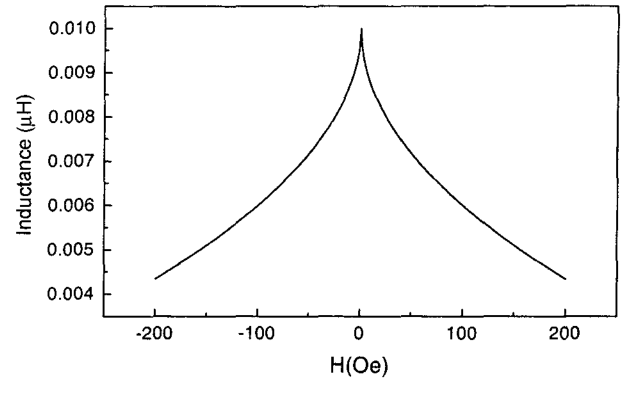

Fig. 2. Calculated inductance as a function of an external field.

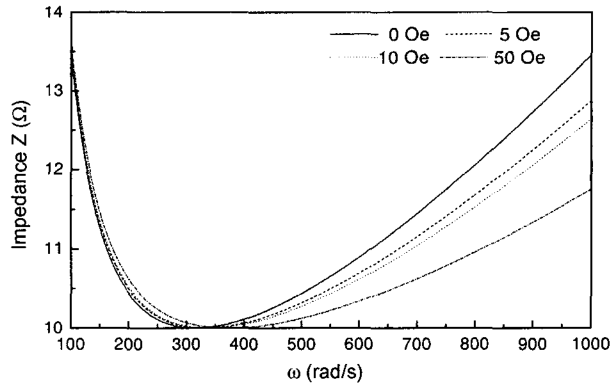

Fig. 3. Calculated impedances as a function of frequency ω at various external fields, $H = 0$ Oe, 5 Oe, 10 Oe, 50 Oe, respectively.

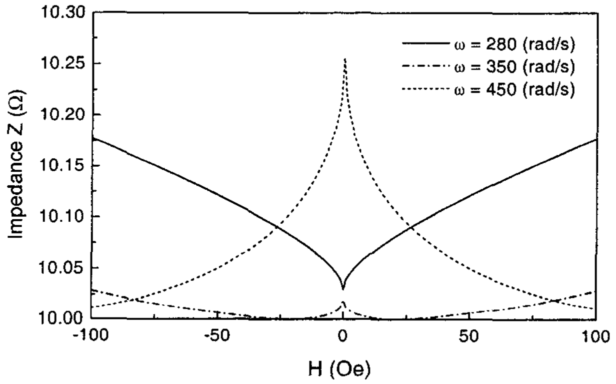

Fig. 4. Calculated impedances Z at different frequencies, $\omega =$ 450 rad/s, 350 rad/s, 280 rad/s, respectively.

(4a) and plotted as a function of frequency at the various intensities of the external dc-field are shown in Fig. 3 where C is taken as 1000 pF. As it can be expected, the impedance at the 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 an 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 it can easily be noticed, the shapes of these simulated magneto-impedance 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, resemble the experimental one obtained at 550 MHz (close to the resonance frequency). The sudden change of the phase angle as large as 180° gives an evidence that the resonance in fact occurs at a specific intensity of the dc-field as shown in Fig. 6.

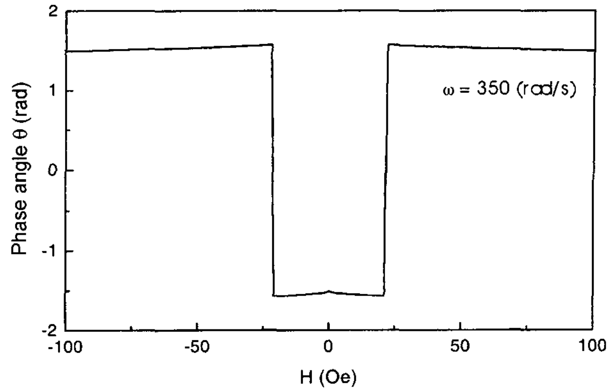

Fig. 5. Calculated phase angle θ curve at a resonance frequency ω of 350 (rad/s).

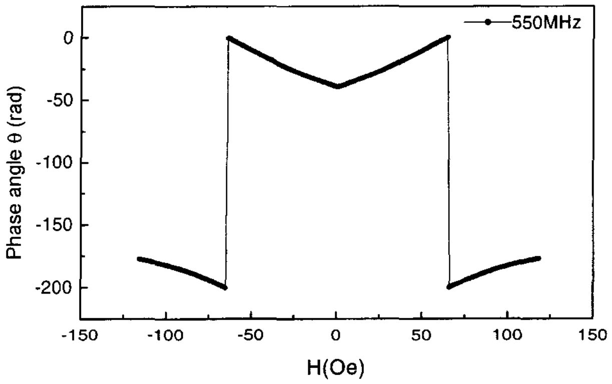

Fig. 6. Phase angle curve measured at 550 MHz.

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 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 magneto-impedance 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).

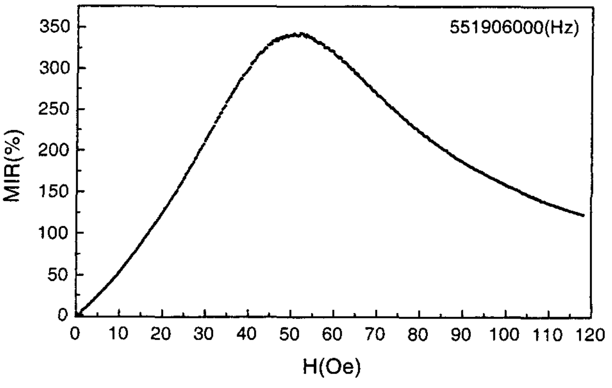

Fig. 7. MIR curve measured at 551,906,000 Hz.

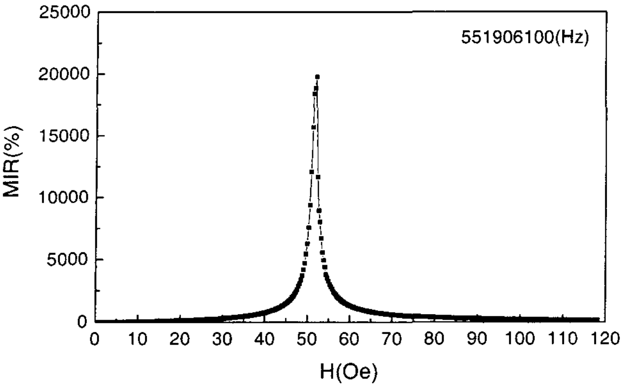

Fig. 8. MIR curve measured at 551,906,100 Hz.

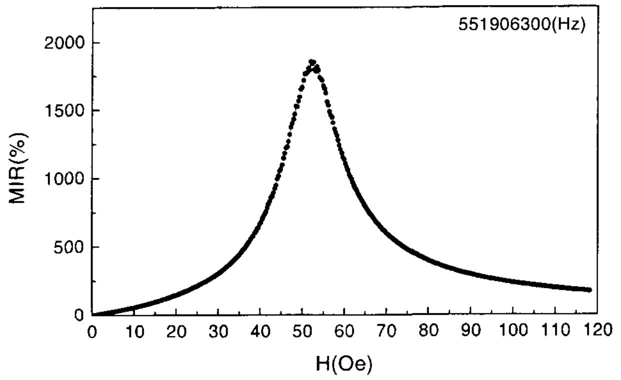

Fig. 9. MIR curve measured at 551,906,300 Hz.

The SGMI effects can be observed by precise tuning frequency around the resonance frequency. The dramatic increment of *MIR* values reached in the experiment as much as 350% at 551,906,000 Hz, 20,000% at 551,906,100 Hz, 2,000% at 551,906,300 Hz, and 450,000% at 551,907,500 Hz, etc., respectively as shown in Fig. 7, Fig. 8, Fig. 9, and Fig. 10. The 450,000% is the best value of *MIR* ever discovered so far.

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 from 100 MHz 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 450,000% at the frequency of around 551.975 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.

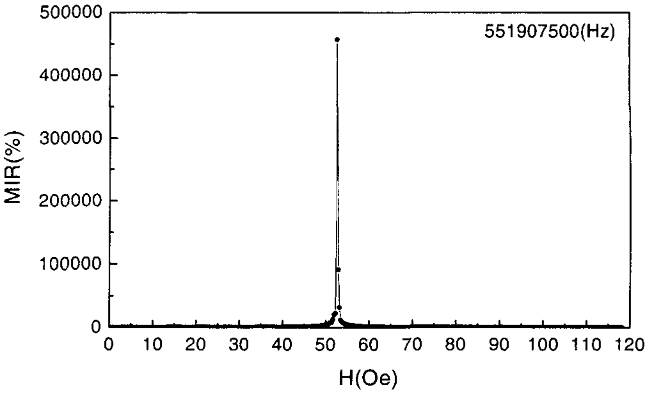

Fig. 10. MIR curve measured at 551,907,500 Hz.

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