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Magneto-resistance, magneto-reactance, and magneto-impedance effects in single and multi-wire systems

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ABSTRACT

A systematic study of the magneto-resistance (MR), magneto-reactance (MX), and magneto-impedance (MI) effects in single and multiple glass-coated amorphous $Co_{68}B_{15}Si_{10}Mn_7$ microwires is reported. Our studies reveal that the MR, MX, and MI ratios and their corresponding magnetic field sensitivities strongly depend on the number of microwires in an array and on the distance between them. We find that increasing the number of microwires increases the MR and MI ratios and their field sensitivities (η_R and η_Z, respectively) but decreases the MX ratio and its field sensitivity (η_X). A similar trend is observed for the frequency dependence of these parameters. Increasing the distance between the wires is also found to decrease the MR and MI ratios but increase the MX ratio of the array considerably. From a sensor application perspective, it is interesting to note that for the case of a single microwire, the η_X reaches a value as high as 960%/Oe at a frequency of 1 MHz, which is about 192 times of the η_R or η_Z (~5%/Oe), revealing the possibility of developing ultrahigh sensitivity magnetic field sensors based on the principle of the MX effect.

1. Introduction

A soft ferromagnetic material experiences a large change in its ac impedance, the so-called magneto-impedance (MI) effect, when an ac current $I = I_0 sin\omega t$ of high frequency flows through it in the presence of an external dc magnetic field [1]. The MI effect has been of increasing interest in sensor technology because of its high sensitivity, quick response, low cost, easy handling, minimal environmental impact, and stability in operation [1–4]. It has been observed in a wide range of soft ferromagnetic materials, such as wires [1,4–9], ribbons [10–12], and thin films [9,13–15].

Different approaches, such as the skin effect [1,8] and equivalent circuit [7], have been proposed to explain the MI behavior of a magnetic conductor. However, it is widely believed that the origin of the MI is associated with the effective permeability in a direction transverse to the applied ac current and dc magnetic field [9,10,15–19]. This permeability is associated with many physical parameters of the magnetic conductor, including magnetostriction, stress, and magnetic anisotropy. Under a linear approximation, the complex impedance $Z=R+iX$ (where R and X are the resistance and reactance, respectively) of the material can be expressed as the ratio of the voltage induced at its ends to the magnitude of the current flowing through it. Under the material approximation, the Z of the material can be related to the effective permeability by solving classical Maxwell's equations [9,16]. For a cylindrical magnetic conductor, the impedance

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

with $k = (1+i)/\delta_m$ is expressed in terms of first kind Bessel functions J_0, J_1 and the material parameters; the skin depth δ_m, the radius a, and the dc resistance R_{dc} of the conductor. The imaginary unit i appears in Eq. (1) to account for the complex nature of the impedance. The effective permeability, the so-called circumferential permeability μ_ϕ for the case of a cylindrical conductor, appears in the expression of the skin depth

$$\delta_m = \sqrt{\frac{\rho}{\pi \mu_\phi f}} \quad (2)$$

where ρ is the resistivity of the conductor and f is the current frequency. The Z expressed in Eq. (1) is a function of external dc magnetic field via the circumferential permeability in Eq. (2). It has been shown that the magnetic field-induced MI ratio falls off at low frequencies, where $a/\delta_m \ll 1$, because the contribution is mainly due

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to the induced magneto-inductive voltage [17]. However, the MI ratio becomes significant at higher frequencies where $a/\delta_m \gg 1$ and the skin effect plays a primary role in contributing to the impedance change [17]. Additionally, one should take into account that both magnetic permeability and magneto-impedance have tensor characters [18].

It has been experimentally shown that soft ferromagnetic amorphous glass-coated microwires are one of the most attractive candidate materials for use in MI-based sensors [1–3,6,19–22]. The suitability of such materials for sensing applications is due to the fact that a small change in the electric and magnetic environment near or on the wire can alter the circumferential permeability to a great extent and hence the large MI ratio. Therefore, several efforts have been made to optimize the MI effect in these microwires through studies of the effects of metallic composition, magnetoelastic anisotropy, magnetostriction, and other geometrical parameters on the MI of the wires [8,19–22]. Interestingly, Garcia et al. [23] reported that both the MI effect and its field sensitivity could be greatly improved in a system consisting of multiple wires in a parallel arrangement. Chiriac et al. [24] showed that this multi-wire system could have a great potential for highly sensitive detection of biomolecules. However, the origin of the observed MI effect and the influence of wire spacing on the MI signal remain to be investigated. From a magnetic sensor application perspective, it is essential to investigate the effects of multi-wire configuration not only on the magneto-impedance (MI), but also on the magneto-resistance (MR) and magneto-reactance (MX) of the system, both of which may provide alternative approaches to develop magnetic sensors with enhanced sensitivity.

To address these important issues, we have performed a systematic study of the MR, MX, and MI effects over a frequency range of 0.1–13 MHz in an array of amorphous glass-coated $Co_{68}B_{15}Si_{10}Mn_7$ microwires. Our studies show that increasing the number of microwires increases the MR and MI ratios and their field sensitivities but decreases the MX ratio and its field sensitivity. Increasing the distance between the wires decreases the MR and MI ratios but increases the MX ratio of the array. The field hysteresis of MR, MX, and MI is found to be independent of the number of wires. These observations are of practical importance in developing singe- and multi-wire systems for advanced sensor technologies.

2. Experiment

An amorphous glass-coated microwire of $Co_{68}B_{15}Si_{10}Mn_7$ was prepared by a glass-coated melt-spinning technique [25]. The metallic diameter of the wire was about 25 μm surrounded by about 7.2 μm thick glass layer. Segments of the wire were arranged in parallel on a non-magnetic glass slab with a separation of 2 mm between each consecutive wire. The number of wires in the array (denoted hereafter as N) was varied from one to five. Four-terminal contacts were made with copper wires using silver paint by removing 6 mm of the glass layer for each high and low terminals. The distance between two inner contacts was 1 cm and each outer contact was 3 mm away from the consecutive inner contact. A dc magnetic field in the range ±120 Oe was applied parallel to the wire axis by placing the arrangement at the center of a homemade Helmholtz coil of 30 cm diameter and connecting to a Kepco bipolar power supply. The impedances of the arrays were measured by using an HP4192A analyzer with a constant ac current of 1 mA supplied along the axis of the wires over a frequency range of 0.1–13 MHz. The MR, MX, and MI ratios are respectively defined as

$$\frac{\Delta R}{R} = \frac{R(H) - R(H_{max})}{R(H_{max})} \times 100\% \tag{3}$$

$$\frac{\Delta X}{X} = \frac{X(H) - X(H_{max})}{X(H_{max})} \times 100\% \tag{4}$$

$$\frac{\Delta Z}{Z} = \frac{Z(H) - Z(H_{max})}{Z(H_{max})} \times 100\% \tag{5}$$

The dc magnetic field sensitivities of the MR, MX, and MI are respectively calculated as

$$\eta_R = 2 \times \frac{[\Delta R/R]_{max}}{\Delta H} \times 100\% \tag{6}$$

$$\eta_X = 2 \times \frac{[\Delta X/X]_{max}}{\Delta H} \times 100\% \tag{7}$$

$$\eta_Z = 2 \times \frac{[\Delta Z/Z]_{max}}{\Delta H} \times 100\% \tag{8}$$

where $[\Delta R/R]_{max}$, $[\Delta X/X]_{max,}$ and $[\Delta Z/Z]_{max}$ are the maximum values of the MR, MX, and MI ratios given in Eqs. (3)–(5) and ΔH is the full width at half maximum of the corresponding ratio *versus* H_{dc} plot.

3. Results and discussion

Fig. 1 depicts the zero-field frequency dependence of resistance (a), reactance (b), and impedance (c) of the microwire arrays with each consecutive wire separated by 2 mm. A clear decrease in the resistance (R), reactance (X), and impedance (Z) is observed as the number of wires (N) in the arrays is increased. As seen in Fig. 1(a), the resistance of each array increases almost linearly with frequency in the range of 0.1–13 MHz. However, the slope of the curves decreases with increasing N, indicating smaller variations with change in the frequency. As observed in Fig. 1(b), the reactance of the entire system increases with frequency for all the arrays. However, there is a noticeable difference in the frequency dependence of the reactance as compared to that of the resistance. At low frequencies (<1 MHz) the behavior of the reactance is al-

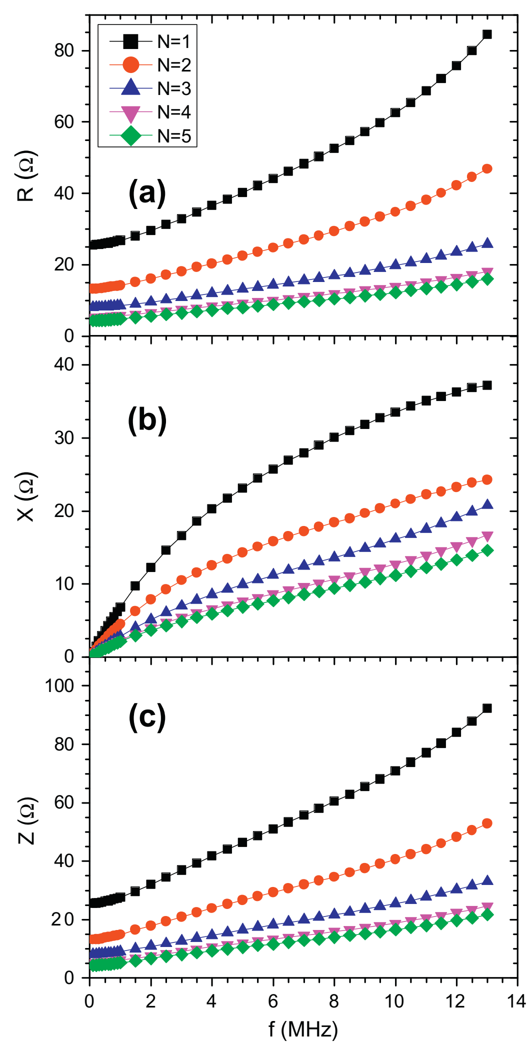

Fig. 1. Frequency dependence of the (a) resistance, (b) reactance and (c) impedance of microwire arrays with different numbers of elements (N).