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Influence of stress on magneto-impedance in $Co_{71-x}Fe_xCr_7Si_8B_{14}$ ($x = 0, 2$) amorphous ribbons

B. Kaviraj [a,*], *S.K. Ghatak* [b]

[a] *LGEP/SPEE Labs, CNRS UMR 8507, Supélec, Universite Pierre et Marie Curie-VI, Universite Paris Sud-XI, 11 rue Joliot-Curie, Plateau de Moulon, 91192 Gif-sur-Yvette, France*
[b] *Department of Physics & Meteorology, Indian Institute of Technology, Kharagpur 721302, India*

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ABSTRACT

Systematic measurements of stress-impedance (SI) have been carried out using Co-rich amorphous ribbons of nominal composition $Co_{71-x}Fe_xCr_7Si_8B_{14}$ ($x = 0, 2$) at various excitation frequencies and bias fields and at room temperature. The impedance, $Z(\sigma)$ for both the samples was found to be very sensitive functions of applied tensile stresses (up to 100 MPa) exhibiting a maximum SI ratio as much as 80% at low frequency ~0.1 MHz. The nature of variation of SI changes with the excitation frequency especially at higher frequencies in MHz region where it exhibits a peak. Magnetization measurements were also performed to observe the effects of applied stresses and magnetization decreased with the application of stress confirming the negative magnetostriction coefficient of both the samples. Both the samples exhibited negative magneto-impedance (MI) when the variation of Z is observed with the applied bias magnetic field, H. The impedance as functions of applied magnetic field, $Z(H)$, decreases with the application of stress thus making the MI curves broader. Maximum MI ratio as large as 99% has been observed for both the samples at low fields ~27 Oe.

1. Introduction

The magneto-impedance (MI) effect is a large change of impedance induced by a dc magnetic field in a soft ferromagnetic conductor and in most situations the impedance is reduced to a large extent compared to that in a zero-field state. The ferromagnetic materials like the amorphous transition metal–metalloid alloys, with the shapes of wires (Panina et al., 1995; Atkinson et al., 1995; Chiriac et al., 1997; Tannous and Gieraltowski, 2004), ribbons (Sommer and Chien, 1996; Sartorelli et al., 1997; Valenzuela et al., 1997; Tejedor et al., 1996) and thin films (Morikawa et al., 1997; Sommer and Chien, 1995) are forerunners in exhibiting large MI at low frequency (Beach and Berkowitz, 1994; Panina and Mohri, 1994; Mandal and Ghatak, 1993; Menard et al., 2000). The Fe- or Co-based metallic glasses in the form of ribbons or wires are magnetically soft and the relative decrease in impedance in presence of small fields is very large (Beach and Berkowitz, 1994; Panina and Mohri, 1994; Mandal and Ghatak, 1993; Menard et al., 2000; Knobel and Pirota, 2002). The MI effect has been observed for as-quenched, amorphous as well as in the nanocrystallized materials (Ueda et al., 1997; Knobel et al., 1996; Tejedor et al., 1998). The MI effect is associated with the field penetration of electromagnetic (e.m.) waves within a magnetic metal of high permeability. The impedance of a metal is determined by the penetration depth of e.m. field and the penetration depth in turn is a measure of the screening of e.m. field. In paramagnetic metals, the screening is solely due to

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[*] *Corresponding author*. Tel.: +33 6 72 58 24 76; fax: +33 1 69 41 83 18.
E-mail address: bhaskar.kaviraj@lgep.supelec.fr (B. Kaviraj).

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the conduction electrons whereas in ferromagnetic metals an additional component of screening arises from ac magnetization. This leads to higher impedance in ferromagnetic state. However, screening of magnetic origin can be altered significantly by changing the magnetic response to ac field. The response, as measured by the dynamic permeability μ, can be altered by applying an external dc magnetic field, external stress, thermal treatment, etc. In most cases, a moderate magnetic field increases penetration depth of the e.m. field at rf range and thereby the impedance is decreased compared to that at zero-field (Costa-Kramer and Rao, 1995; Shen et al., 1997). The permeability of a ferromagnetic substance is governed by the magnetic anisotropy energy. The external stress can modify the anisotropy in a material with non-zero magnetostriction coefficient and therefore induce a change in impedance—referred as stress-impedance (SI) (Mohri et al., 1995; Machado et al., 1995; Wun-Fogle et al., 1987). The Co-rich ferromagnetic amorphous alloys have high permeability, low magnetic losses and low magnetostriction constant, and these make the materials suitable for observing both SI and MI effects (Mohri et al., 1995; Machado et al., 1995).

In this communication, the influence of stress on magneto-impedance and magnetization are studied for the sample $Co_{71-x}Fe_xCr_7Si_8B_{14}$ ($x = 0, 2$) at different excitation frequencies and bias fields. The amorphous ribbons with the above composition possess very low and negative magnetostriction. This facilitates the observation of very large and sensitive changes in magneto-impedance with the application of an external dc field and as such is very useful for employment in magnetic field sensors (Wun-Fogle et al., 1987; Barandiaran and Gutierrez, 1997). Commonly Fe-rich amorphous alloys in the form of thin ribbon and with high positive magnetostriction ($\lambda_s \sim +30$ ppm) are very suitable for mechanical stress sensors. Nevertheless they can be used only for relatively small strain range because of the saturation effect. When the desired range of strain measurement is more than 1000 ppm, the amorphous alloys with negative magnetostriction are preferable (Kraus et al., 2002). Amorphous alloy with a higher content of Cr (7 at.%) possesses high corrosion resistance and small temperature coefficient which suits them in the application of magnetoelastic sensors for strain and load measurements in civil constructions (Kraus et al., 2002).

2. Experimental details

Amorphous ribbons with nominal compositions $Co_{71}Cr_7Si_8B_{14}$ and $Co_{69}Fe_2Cr_7Si_8\ B_{14}$ were produced using the melt-spinning technique. The sample cross-sections were 6.41 mm × 0.0335 mm and 6.347 mm × 0.0325 mm, respectively. All the samples were cut in 8 cm long pieces for the measurements. All the samples were used in as-quenched state and were aligned with their longitudinal axis perpendicular to the Earth's magnetic field. The samples were placed within a small signal coil of rectangular geometry and with 100 turns. The coil was located at the middle of the sample-length which was longer than the length of the coil in order to reduce the demagnetization effects due to ac excitation field. The coil was connected to the current terminal of the Impedance Analyzer (Model-HP4294A) where a sinusoidal current amplitude was kept constant at $I_{rms} = 20$ mA. This created an ac magnetic field of about 196 A/m along the axis of the coil which is also along the length of the ribbon. The voltage response of the sample around this field was found to be linear. The frequency of the driving current was scanned from 100 kHz to 10 MHz. Maximum dc bias fields up to 27 Oe was applied parallel to the exciting ac field and along the length of the ribbon. Magnetization measurements were performed with the help of an ac magnetometer at 70 Hz frequency.

These samples were further subjected to tensile stresses using load and pulley arrangement. Maximum stresses up to 100 MPa were applied in the longitudinal direction (which is also the direction of exciting ac field) depending upon the cross-section of the ribbon. The real and imaginary components of impedance $Z = R + jX$ where $X = \omega L$ (L being the inductance of the sample) were measured across the signal coil with the help of Impedance Analyzer. The resistance and reactance of the empty coil and test leads were subtracted and only the change in impedance due to the sample was taken into account. All measurements were performed at room temperature. The stress-impedance ratio has been expressed as:

$$\delta Z_\sigma\% = \frac{Z(\sigma) - Z(0)}{Z(0)} \times 100 \qquad (1)$$

3. Results

3.1. *Sample $Co_{71}Cr_7Si_8B_{14}$ ($x = 0$)*

Fig. 1 shows the excitation frequency response of the resistive (R) and reactive (X) components of impedance for the sample $Co_{71}Cr_7Si_8B_{14}$ as functions of different external tensile stresses. At all stresses, R and X are low at low frequencies but increase monotonically at higher frequencies. The reactive part is greater than the resistive part. The applied tensile stress (σ) decreases the magnitude of R progressively as the stress is increased from 0 to 100 MPa. The frequency response of the reactive component of Z on the other hand exhibits a 'cross-over' in high frequency region (>1 MHz) at $\sigma = 20$ MPa where it crosses the 'zero-stress' curve indicating that the values of X at 20 MPa stress are greater than those at 'zero-stress' in this frequency region. But at $\sigma = 100$ MPa, the values of X are lower than those at $\sigma = 0$ MPa. These will be clear from the results of stress-impedance measurements that are presented subsequently.

In Fig. 2, we show the stress-impedance results for the sample $Co_{71}Cr_7Si_8B_{14}$ measured at different excitation frequencies of 0.1, 1 and 10 MHz. Here the percentage change in impedance $\delta Z_\sigma\%$ has been plotted as functions of different tensile stresses. At low frequencies, the impedance depicts a maximum at zero-stress and falls off sharply with the increase of stress. At a higher frequency (10 MHz), the impedance increases with stress and exhibits a maximum at $\sigma \sim 20$ MPa and $\delta Z_\sigma\%$ becomes negative at higher stresses. The maximum relative change in SI decreases from 80% (0.1 MHz) to around 40% (10 MHz) with the increase in frequency in the range of applied stresses.