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Analysis of the off-diagonal component of giant magnetoimpedance effect in Co-based (as-cast and stress-annealed) amorphous ribbons

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A B S T R A C T

We investigated the effect of the application of dc bias current I_B on the off-diagonal magnetoimpedance (MI) components at 50 MHz in nearly-zero magnetostrictive $Co_{66.5}Fe_{3.5}Si_{12.0}B_{18.0}$ amorphous ribbons in as-cast and stress-annealed state. The off-diagonal MI component is anti-symmetrical with near-linear behavior within a certain field interval. For the off-diagonal response, the dc bias current is necessary to eliminate transverse domains present in the ribbon. A highly asymmetry of the off-diagonal dependence with the axial magnetic field was obtained when the bias current is applied along the ribbon. A rather high slope at the zero-field point was obtained, being more pronounced in the stress-annealed samples. This is probably related with the domain structure reorganization under the effect of the bias current. This behavior is ideal for a practical sensor circuit design.

1. Introduction

Giant magnetoimpedance (GMI) effect is basically the significant change in the complex impedance of a magnetic conductor, under the application of an external DC magnetic field. Since the GMI effect was discovered in 1992 [1,2], it has been widely studied in soft magnetic wires [3,4], ribbons [5,6], thin films [7,8], glass-coated microwires [9,10] and composite structure [11], because of its prospective applications in magnetic sensor elements. Co-based amorphous ribbons with excellent soft magnetic properties have been regarded as one of the candidates of high-performance magnetic sensors [12,13].

Recently, we have investigated the GMI in $Co_{66.5}Fe_{3.5}Si_{12.0}B_{18.0}$ amorphous ribbons in as-cast state [14] and with stress induced magnetic anisotropy developed submitting the ribbon to stress-annealing treatment [15]. In both papers was analyzed the role of the distribution of the transverse magnetic anisotropy through the cross section affecting drastically to the GMI response (intensity and external magnetic field associated to the appearance of the two peaks). Obviously, the GMI effect was improved in the stress-annealed ribbon, which is more intensive in value with narrower and sharper peaks associated to a higher transverse susceptibility comparing with the as-cast ribbon. This aspect is very important regarding the future applications of this material. In this point it must be noted that the longitudinal impedance has appeared generally not to be suitable for magnetic sensors applications as it exhibits a symmetric dependence on the magnetic field. Such dependence is almost insensitive (a zero slope) at the zero-field and does not allow determination of the direction of applied magnetic field.

It is remarkable the significant progress in longitudinal MI sensor development, and the off-diagonal MI effect that appears due to the cross-magnetization process [16–18] has turned out to exhibit better characteristics and actually is used in commercially available MI sensors [5]. Such an off-diagonal MI sensor allows determination of both the magnitude and the sign of external magnetic field.

In this work we present the recent results on the longitudinal and off-diagonal magnetoimpedance response components obtained in near-zero magnetostriction Co-based amorphous ribbons in as-cast and stress-annealed state. Experimental results of these components have been obtained at 50 MHz, which is a frequency value quite far of the GHz range where the ferromagnetic resonance effect is predominant. The effect of a bias current, I_B, on these magnetoimpedance components has been analyzed giving useful information from the asymmetric character of such components.

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2. Experimental details

Off-diagonal $Z_{\varphi z}$ impedance component was measured in 1 cm long piece of amorphous ribbon with nominal composition $Co_{66.5}Fe_{3.5}Si_{12.0}B_{18.0}$ fabricated by the melt-spinning technique using a Fe wheel. Different pieces of ribbon were submitted to the following stress-annealing treatment:

(a) Sample 1: as-cast sample.
(b) Sample 2: tensile stress annealing at 400 °C with 300 MPa during 1 h, without pre-annealing.
(c) Sample 3: pre-annealing at 340 °C during 1 h, followed by a tensile stress annealing at 340 °C with 300 MPa during 1 h.
(d) Sample 4: pre-annealing at 340 °C during 1 h, followed by a tensile stress annealing at 340 °C with 200 MPa during 1 h

In all treatments the tensile stress was applied along the ribbon axis. More details on the magnetic parameters of the as-cast and annealed ribbons can be found in Refs. [6,14] and references there in.

The samples were measured in a specially design micro-strip sample holder. A transversal bias field, $H_{B,}$ was created by a dc bias current I_B applied to the samples through a bias-tee element. The amplitude of bias current, I_B, was small to prevent the samples overheating and crystallization. The impedance components Z and $Z_{\varphi z}$ were measured simultaneously using vector network analyzer (VNA) at the frequency of 50 MHz. The off-diagonal impedance $Z_{\varphi z}$ was measured as transmission coefficient S_{21} as a voltage induced in a 2-mm long 10 turns pick-up coil wound over the ribbon. Fig. 1 shows simplified schematics of the off-diagonal measurement setup. All experimental results show both ascending and descending branches of the field dependencies of the real part of impedance Z' and $Z'_{\varphi z}$ so that the magnetic hysteresis can be evaluated. An external magnetic field (up to 15 kA/m) was applied along the longitudinal direction of the ribbon.

3. Results and discussion

It is known that the off-diagonal impedance component is very sensitive to the surface domain structure. In fact, this component arises from the presence of a non-axial anisotropy [17]. Therefore we measured it with different values of the bias current as it is shown in Fig. 2. For $\boldsymbol{I_B}$ = 0 mA, $Z_{\varphi z}(H)$ behaves in a similar way to that found in glass-coated microwires [19], displaying two similar branches with different sign according to the direction of the applied magnetic field. In addition, both branches have a maximum (or minimum) around 600 A/m which is similar to the maximum of the longitudinal Z component and, therefore, with the average magnetic anisotropy field. It is interesting to note the quite large linear region around H = 0 A/m, that is $dZ_{\varphi z}/dH$ to be constant, which is an important requirement thinking on future applications.

When I_B is applied, the two $Z_{\varphi z}(H)$ branches with different sign with a remarkable asymmetric character appear as I_B is increased, even $Z_{\varphi z}(H) = 0$ for H different to zero, and, consequently, the maximum (or minimum) are obtained at different value of applied magnetic field with lost of linearity around H = 0 A/m. If a high I_B is applied (> 250 mA), the $Z_{\varphi z}(H)$ is, surprisingly, positive in both branches with maximum in

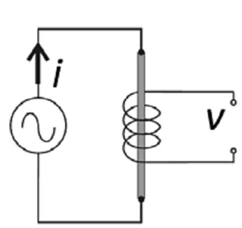

Fig. 1. Simplified schematics of off-diagonal measurement setup.

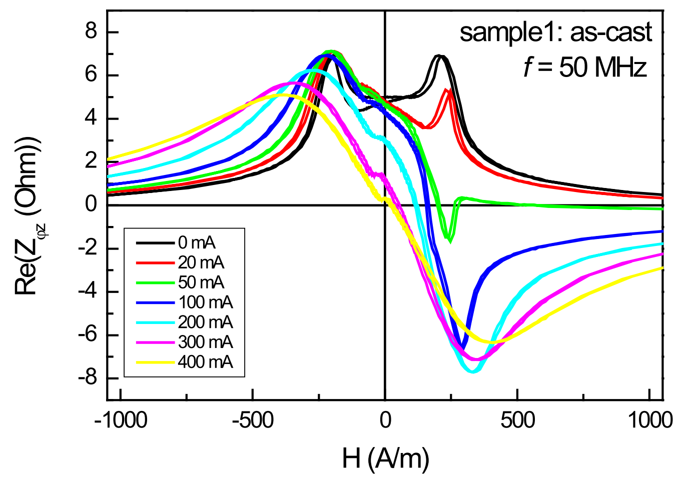

Fig. 2. Off-diagonal impedance component of the as-cast amorphous ribbon as a function of the axial applied magnetic field.

both directions of the axial magnetic field that suggests that the domain structure is almost removed, although some asymmetry could be related with different surface anisotropy in both sides of the ribbon [20]. With a lower I_B the dependence exhibits a higher degree of asymmetry, probably related with a high DW width that suggest existence of a predominant magnetization orientation in one of the transversal direction.

Fig. 3(a–c) shows the real part of off-diagonal impedance $Z_{\varphi z}(H)$ $S_{21}(H)$ measured at 50 MHz with different dc bias currents I_B for stress-annealed samples. If no dc bias current, I_B, is applied, the response signal is very small and irregular. It increases substantially when a small dc current is applied. Typically, the coercivity in amorphous ribbons is about a fraction of one Oersted and applying a small current of a few milliamp transverse domains are eliminated. Therefore, in the case of a transverse induced anisotropy and domain structure transversally oriented to the ribbon axis, the presence of transverse domains is the necessary condition, as has been previously mentioned, for the existence of the off-diagonal components of the impedance tensor. The amplitude of bias current I_B was small to prevent the ribbon overheating and crystallization. For I_B = 0, the off-diagonal impedance shows symmetric peaks for applied field values in the vicinity of the anisotropy field, H_K, for each stress-annealed ribbon. In this case, the total response should be zero for all field range; however, these symmetric peaks are due to the small residual like-helical anisotropy, which remains in the samples after been submitted to stress annealing [15]. With I_B = 100 mA, the off-diagonal response significantly increases (see Fig. 4) and becomes antisymmetric with respect to the field H, having almost linear behavior in the field range of 500 A/m, for the three stress-annealed samples. This behavior can be explained as follows. The transverse dc field created by the bias current makes one or the opposite (depending on the current direction) transverse magnetization direction more favorable. Domains with magnetization lying along the bias field increase at the expense of domains with magnetization aligned against this field. If it is sufficiently large, domains with magnetization lying along the bias field collapse forming a single domain structure. Then, both the axial external magnetic field and the transverse dc bias field determine the re-magnetization process [17,18]. Besides, if this field is sufficiently high, the field dependence of the off-diagonal impedance becomes asymmetric and anhysteretic [21] as it is shown in Fig. 3. The quasi-linear behavior near H = 0 of $Z_{\varphi z}(H)$ is rather interesting for field sensors [21].

The variation of the maximum $\mathrm{Re}Z_{\varphi z}(H)$ with I_B of the stress-annealed ribbons is displayed in Fig. 5. As it can be seen, the value of the maximum $\mathrm{Re}Z_{\varphi z}(H)$ increases as I_B increases up to reach a maximum depending of the induced magnetic anisotropy. As it was demonstrated