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LETTER TO THE EDITOR

Stress dependence of the giant magneto-impedance effect in amorphous wires

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Abstract. The recently discovered giant magneto-impedance (GMI) effect has been measured as a function of circular driving-field frequency and applied tensile stress on two near-zero-magnetostriction amorphous wires. The effect of different orientations of the induced magnetoelastic anisotropy has been verified, for the first time, by using wires with opposite magnetostriction constant, λ_S, signs ($Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$, $\lambda_S = 1.5 \times 10^{-7}$; and $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$, $\lambda_S = -4 \times 10^{-8}$). GMI ratios up to 300% were found in the magnetically softer (lower-magnetostriction) wire. The frequency dependence of GMI has been found to be strongly influenced by the magnetoelastic anisotropy induced in the amorphous wires. Results are interpreted in terms of changes in the magnetic penetration depth by modifications in the circumferential permeability originated by the action of external agents as field and mechanical stresses. GMI is therefore found to be largely determined by the magnetic domain configuration and relative contributions of both domain wall motions and magnetic moment rotations to the overall magnetization process.

Soft ferromagnetic amorphous wires display several striking physical properties mainly caused by their peculiar fabrication method. As a result of the 'in-rotating-water' quenching procedure, amorphous wires possess a well defined internal stress distribution which determines the domain structure and its response to applied magnetic fields [1]. Low-field magnetic bistability is spontaneously observed in Fe-rich materials and accurately treated low-magnetostrictive Co-based alloys [2]. A large variety of pulse and magnetoelastic effects such as the Matteuci effect, the inverse Wiedemann effect, and the enhanced ΔE effect, have continuously demonstrated the enormous potential of amorphous wires in sensor applications [3]. More recently, a new and notable effect was first observed in low-magnetostriction wires [4–6] (and afterwards also in amorphous ribbons [7, 8]), the so-called giant magneto-impedance effect (GMI). Applying an axial DC magnetic field, the variations of the wire impedance in a high-frequency region (above 100 kHz) were found to reach values up to 200% [9, 10]. Furthermore, the sensitivity to the applied field was observed to be remarkably large, with maximum slopes of 1700% Oe^{-1} [9]. The field induced variations on the materials' impedance are impressive, if compared to the best DC magneto-resistive ratios reached by multi-layered films or granular materials [11].

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The variation of the magnetic penetration depth at a given frequency caused by an external magnetic field is responsible for the strong changes in the impedance of the considered magnetic material [5, 12]. Although the magneto-impedance effect has a classical electromagnetic origin [5, 6, 12], it is difficult to explain owing to the complex magnetic response of the domain configuration to external excitations. Hence, the study of the influence of external agents on the GMI is fundamental to clarify the basic mechanisms underlying this phenomenon, and also to tailor better application oriented materials.

In this letter, we present the first investigation about the influence of magnetoelastic anisotropy on the GMI effect. The magnetoelastic anisotropy is systematically varied by applying axial tensile stresses on amorphous wires with small either positive or negative magnetostriction. The frequency dependence of GMI suffers great changes by applying longitudinal stresses, depending on the sign and amplitude of the magnetostriction constant. The observed trend is explained considering the basic stress- and frequency-dependent magnetization processes occurring within the amorphous wires.

Our experiments were performed on nearly non-magnetostrictive wires, kindly supplied by Unitika Ltd. Two wire compositions were analysed: (a) $Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$, diameter $2R = 1.25 \times 10^{-5}$ m, saturation magnetostriction constant $\lambda_S = 1.5 \times 10^{-7}$; and (b) $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$, diameter $2R = 1.24 \times 10^{-5}$ m, which has a slightly negative $\lambda_S = -4\times10^{-8}$. The ends of 4.5×10^{-1} m long wires were clamped to allow the application of tensile stress σ, and sinusoidal AC current. The voltage across a resistor connected in series to the wire was continuously monitored in order to keep the current amplitude constant ($J_{rms} = 10\times10^{-3}$ A). This current creates a circumferential field given by $H_\phi = Ir/(2\pi R^2)$, where r is the distance to the wire axis. A DC magnetic field of 100 Oe was applied by a long solenoid. We report the variation of the wire impedance after the application of the longitudinal field; $\Delta Z \equiv Z(H = 0 \text{ Oe}) - Z(H = 100 \text{ Oe})$.

Axial hysteresis loops were measured by a conventional impedance technique, for an axial driving field frequency of 300 Hz. The remanence and coercivity obtained from the hysteresis loops are shown in table 1. As expected for positive magnetostriction materials, the remanence of the loops increases with increasing tensile stress. The opposite behaviour is observed in the negative magnetostriction wires. From the table it is also possible to verify the influence of the magnetostriction constant on the magnetic properties of the amorphous wires. The $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ wire displays lower coercive field and lower remanence values than the $Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$ wire, which has higher λ_S absolute value.

Table 1. Magnetic parameters for both studied wires as obtained from axial (M_Z–H_Z) and circumferential (M_ϕ–H_ϕ) hysteresis loops as a function of applied tensile stress.

	$Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$ $\lambda_S > 0$		$Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ $\lambda_S < 0$			
	$M_Z - H_Z$		M_Z–H_Z		M_ϕ–H_ϕ	
σ (MPa)	H_c (mOe)	J_r (mT)	H_c (mOe)	J_r (mT)	H_c (mOe)	J_r (mT)
0	93	421	71	377	33	234
100	108	586	71	377	39	290
180	105	641	64	135	35	293
420	126	654	68	45	48	299
580	144	654	3	6	59	305
740	155	656	—	—	—	—

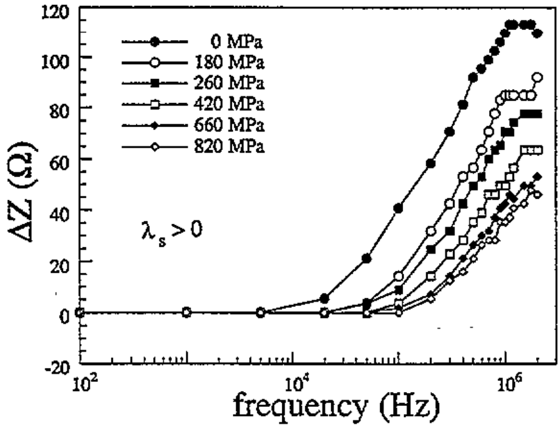

Figure 1. Frequency dependence of the magneto-impedance effect for different longitudinal stresses applied in the $Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$ amorphous wire. $\Delta Z \equiv Z(H = 0\ \mathrm{Oe}) - Z(H = 100\ \mathrm{Oe})$.

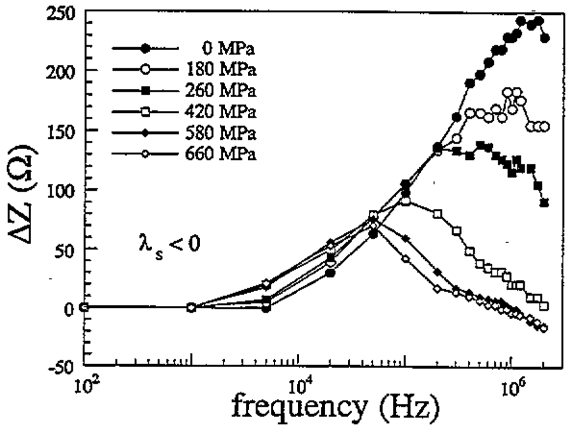

Figure 2. Same as previous figure, for the $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ amorphous wire.

Figure 1 displays the frequency dependence of ΔZ for increasing applied stresses on the positive magnetostriction wire. For low frequencies, the impedance does not change with the application of the external field since the magnetic penetration depth, δ, is larger than the wire radius. At a critical frequency, f^*, the application of the axial field begins to change the impedance. The critical frequency can be immediately found from the condition $R/\delta = 1$ (R being the wire radius), which gives [5, 12]

$$f^* \propto \frac{1}{(2\pi)^2} \frac{\rho}{R^2 \mu_\phi} \tag{1}$$

where ρ is the DC resistivity and μ_ϕ is the circumferential permeability ($B_\phi = \mu_\phi H_\phi$). Hence, the critical frequency increases with the decrease of the circumferential permeability, a situation which is expected by applying a tensile stress in a positive magnetostriction wire. In this case, both the stress and magnetic field act to increase the volume of the axially oriented domains. With increasing stresses the relative changes in the impedance with and without applied field are continuously reduced (see the reduction of ΔZ in figure 1).

The maximum magneto-impedance ratio $\Delta Z/Z$ obtained for the unstressed state of the $Fe_{4.9}Co_{71.8}Nb_{0.8}Si_{7.5}B_{15}$ wire is 180% for $f = 500$ kHz, where we define $\Delta Z/Z \equiv [Z(H = 0 \text{ Oe}) - Z(H = 100 \text{ Oe})]/Z(H = 100 \text{ Oe})$. In the case of the $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ wire, this ratio reaches values up to 300% (for 300 kHz), which is, to our knowledge, among the largest values ever reported in long wires. This difference is related to the absolute value of the saturation magnetostriction constant, which, in amorphous materials, is decisive in the magnetic behaviour of the system. Owing to the lack of magnetocrystalline anisotropy, the magnetic softness of the amorphous wires is mainly determined by magnetoelastic contributions. Lower absolute magnetostriction values lead to higher effective susceptibilities, i.e., the domain walls move more freely. High susceptibilities can be more easily reduced (with enhanced relative change) by the application of an external magnetic field. This obviously increases the magneto-impedance effect.

Figure 2 shows the frequency and stress dependence of ΔZ for the negative magnetostriction wire. In the unstressed state there is a maximum in ΔZ for high frequencies, which displaces towards lower frequencies and reduces amplitude with increasing σ. The value of f^* does not change so clearly as the previous case, probably due to the lower λ_S absolute value, and considering the reduced number of experimental points, it seems to decrease for low applied stresses.

Interpretation of the experimental curves is rather complex, because the wire impedance depends on the frequency f and the effective magnetic permeability, which, in turn, depends not only on the anisotropies present in the material (by applying stress, or by annealing), but also on the frequency itself [12]. It is important to separate the low- and high-frequency regions in the GMI effect. The total magnetic permeability can be separated into contributions from domain wall motion (μ_{dw}) and magnetic moment rotation (μ_{rot}). For high frequencies, the domain wall motion is strongly damped owing to eddy currents, and the rotational contribution to the permeability becomes dominant. In the low-frequency range ($R \ll \delta$), changes in the reactance completely dominate the magneto-impedance effect, and simple models can be used to describe the observed trends [6, 13]. In the high-frequency case, both resistive and inductive components of the impedance contribute to the GMI behaviour as a function of applied field and stress [5, 12].

The frequency dependence of ΔZ of both wires in the unstressed state is very similar, without considering the differences in the amplitudes, discussed previously. The ΔZ values reflect the decrease in the circular permeability caused by the application of a strong axial magnetic field, leading to an increase in the skin penetration depth, and consequently a strong change in the total impedance. The impedance increases with increasing frequency [5], but at high f values the rate of increase is reduced due to the reduction in the effective circular permeability. The curves $Z(f, H = 0 \text{ Oe})$ and $Z(f, H = 100 \text{ Oe})$ have a point of maximum difference, indicated by the well defined peak at about 1 MHz. The stress dependence of the magneto-impedance effect can be interpreted in the light of the major role played by the dominant type of domain configuration on the value of the magnetic permeability [14]. Let us discuss each case separately:

(i) $\lambda_S > 0$: The applied stress acts to increase the uniaxial magnetic anisotropy (as the longitudinal field), and a pattern of predominantly longitudinal domains appears. The corresponding domain walls have very low mobility under a circular driving field generated by the AC flowing in the wire. Consequently, the circular magnetic permeability results mainly from magnetization rotation. The rotation processes are hindered with further

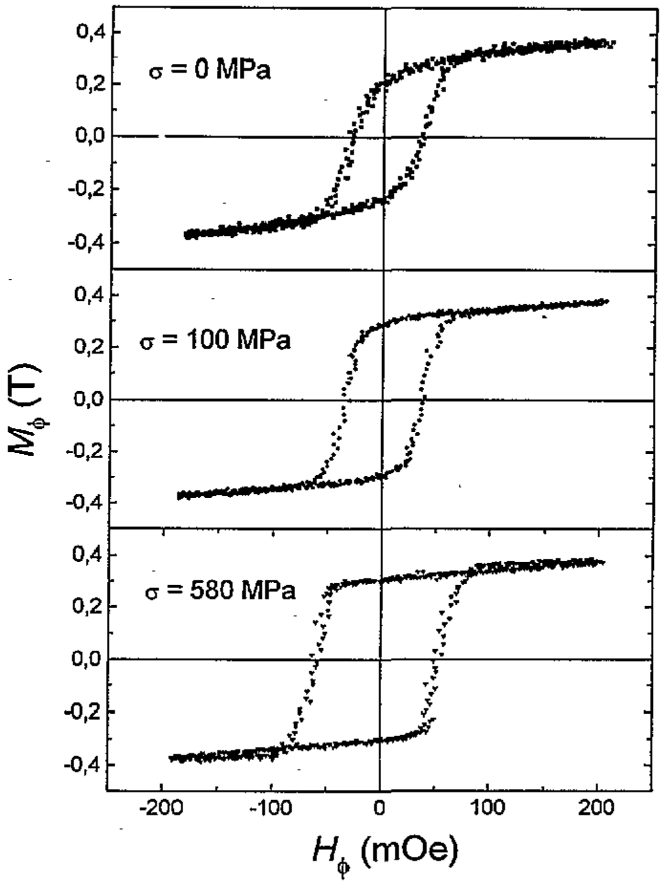

Figure 3. Circumferential AC hysteresis loops $M_\phi - H_\phi$ of $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ amorphous wire for some values of applied stresses.

increasing of the applied stress, owing to the high anisotropy of magnetoelastic nature. Therefore, the circular permeability is strongly reduced. As the rotational term begins to dominate in the permeability value, the peak at high frequencies in the magneto-impedance curves disappears, and the slope of the curves increases for high σ values (see figure 1).

(ii) $\lambda_S < 0$: The longitudinal stress promotes the development of transverse domains, while the DC bias field applied along the wire axis acts to increase the number of planar domain walls aligned parallel to the field. The pattern of alternating left- and right-handed circumferential domains largely enhances the role of 180° wall displacements in the circular magnetization process. However, for high frequencies the wall mobility is extremely reduced, resulting in a very strong decrease in the magnetic permeability. In the high-stress region, the predominance of μ_{dw} appears in the strong dependence of the magneto-impedance on frequency. The number of domains decreases, and their widths increase with stress, reducing the f value at which the eddy current damping becomes clearly visible.

This picture is consistent with the axial magnetization processes, measured as a function of applied tensile stress (see table 1). Circular M_ϕ–H_ϕ loops were also measured for the negative magnetostriction wire at 300 Hz with constant current amplitude $I_{rms} = 6$ mA.

The experimental set-up is described in detail elsewhere [15]. Figure 3 shows some representative loops, where the field H_ϕ is the average circular field. The results obtained for the circular coercivity and remanence are also reported in table 1. The circular hysteresis increases with stress, contrary to the axial hysteresis, which flattens with higher σ.

In conclusion, the magnetization processes of ferromagnetic amorphous wires are largely dependent on magnetoelastic anisotropies, even in materials with extremely low magnetostriction constant. Quenched-in and applied stresses play a basic role in determining domain structure and hysteresis, a feature that can be exploited to improve magnetic responses to specific applications. In the case of the GMI, the maximum variation of impedance induced by a magnetic field appears at a certain frequency, which is dependent on the applied longitudinal stress, and results from modifications in the magnetic penetration depth. In fact, the additional magnetoelastic anisotropy term introduced by the uniaxial stresses brings about changes in the domain configuration and its response to a circular driving field. The stress and frequency behaviour of the GMI effect is therefore a direct consequence of changes in the relative contributions of both domain wall motions and rotations to the total circular permeability.

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