Giant magnetoimpedance in nonmagnetostrictive amorphous wires

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The inductive voltage of a Co-based water-quenched amorphous wire has been measured as a function of applied axial dc field, tensile stress, and twisting, when an ac current flows through it. The results show that the giant ac magnetoresistance recently reported for nonmagnetostrictive amorphous wires is actually a giant magnetoimpedance (GMZ). The origin of GMZ in such wires is their large circular susceptibility at high frequencies, which is related to their small magnetostriction and special domain structure.

The magnetoresistance (MR) is popularly referred to as the relative change in resistance of a sample by changing the applied field. The search for materials exhibiting a giant magnetoresistance (GMR, with MR up to 50%) is certainly a topic of major interest mainly due to their enormous possibilities in the field of technological applications. Most of the previous works on this concern magnetic-nonmagnetic multilayered and granular systems.[1,2] In these materials, the scattering of conducting electrons can be largely enhanced by the interaction between their spins and local magnetization of different scattering centers. Recently, a few works[3,4] were published dealing with the effect in single-phase Co-based ferromagnetic amorphous wires. Mandal and Ghatak[3] reported a large ac (82 Hz) magnetoresistance of 12% at room temperature for a sample subjected to a given tensile stress; Machado *et al.*[4] showed a giant ac (100 kHz) magnetoresistance of 27%. Both works explained their results based on mechanisms for true resistance. The obtained values in samples exhibiting an almost zero magnetostriction are two or three orders of magnitude larger than MR reported for highly magnetostrictive Fe-rich amorphous wires,[5] and are quite interesting for applications in new magnetic sensors and magnetic recording heads.[6,7]

On the other hand, another ac effect, the magnetoinductive effect, has recently been reported by Mohri *et al.*[8] for the same type of wires. When an ac current flows through the wire, its high circular susceptibility will enhance the flux produced by the current, so that the self-inductance will be greater than that of a nonmagnetic wire. Since the susceptibility is a strong function of axial applied field, a large change in the inductance induced by a changing field is expected. A theoretical analysis on this conventional effect was given by Hernando and Barandiarán.[9] Due to such an effect, in actual ac measurements, the voltage across the wire should always have two contributions. The Ohmic voltage has the same phase as the current and it is not sensitive to frequency, while the inductive voltage has a $\pi/2$ phase preceding the current and increases with increasing frequency. In Ref. 10, we have confirmed by dc and 82-Hz in-phase ac measurements that Co-rich wire does not have a large MR. In this paper, we will emphasize the inductive contribution and show that the GMR in amorphous wires is actually a giant magnetoimpedance (GMZ).

Our experiments were performed on a water-quenched $Co_{68.1}Fe_{4.4}Si_{12.5}B_{15}$ amorphous wire, kindly supplied by Unitika Ltd., which had a diameter $2r = 0.124$ mm and a length $l = 31.8$ cm. Longitudinal dc magnetic field was applied by a long solenoid. The ends of the wire were clamped to apply tensile and torsional stresses and a triangular ac current as well. The maximum current, around 6.5 mA (rms), flowing through the wire could not increase its temperature more than 5 °C.[11] In order to eliminate the Ohmic voltage from the inductive one a 1:1 resistance Wheatstone bridge was used.[9,12]

Several works have been done on the magnetic behavior of this Co-rich amorphous wire.[11–14] They are magnetically very soft with saturation magnetic polarization $\mu_0 M_s = 0.8$ T, coercivity $H_c \approx 2$ A/m, and saturation magnetostriction constant $\lambda_s \approx -0.4 \times 10^{-7}$ at room temperature. They do not exhibit spontaneous magnetic bistability as in the case of highly magnetostrictive amorphous wires but present a roughly axial easy axis in the region close to the axis and roughly circumferencial easy directions in the rest of the volume.

Figures 1(a) and 1(b) show the dependence of the rms inductive voltage V_{rms} at 82 Hz as a function of the dc applied field H_a for $I_{rms} = 0.65$ and 6.54 mA, respectively, under different applied stresses. We see that there is not a proportionality between V_{rms} and I_{rms}, which is obviously related to the nonlinear and cyclical magnetization in the ferromagnetic wire. Without applied stresses, the application of H_a expands the region where the magnetization is oriented parallel to the axis of the wire, so that the region with circular magnetization is suppressed. Therefore, V_{rms} decreases with increasing H_a at both values of I_{rms}. The application of a tensile stress will produce easy axes perpendicular to the axis of the wire, owing to the negative λ_s, and so expand the region with circular magnetization, which corresponds to the increase of V_{rms}. This is consistent with the results given in Ref. 3 for GMR. The effect of twisting is more complicated: At small I_{rms} [Fig. 1(a)], the application of twist decreases very much V_{rms}, whereas at large I_{rms} [Fig. 1(b)], it increases or decreases V_{rms} depending on the value of H_a. This may be explained as follows. A twist is equivalent to a tensional and a compressive stress mutually perpendicular and at 45° with the axis of the wire. Since both stresses are very large, a large 45° twisted stress anisotropy appears even for the wire

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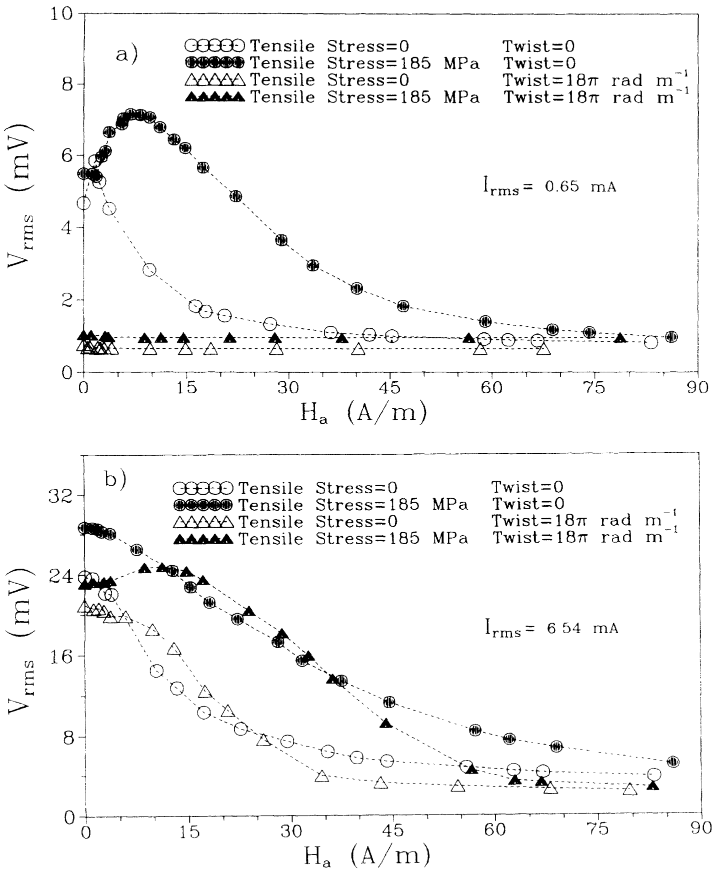

FIG. 1. Inductive voltage V_{rms} at $I_{\mathrm{rms}} = 0.65$ (a) and 6.54 mA (b) as a function of axial dc field H_a for various stress conditions.

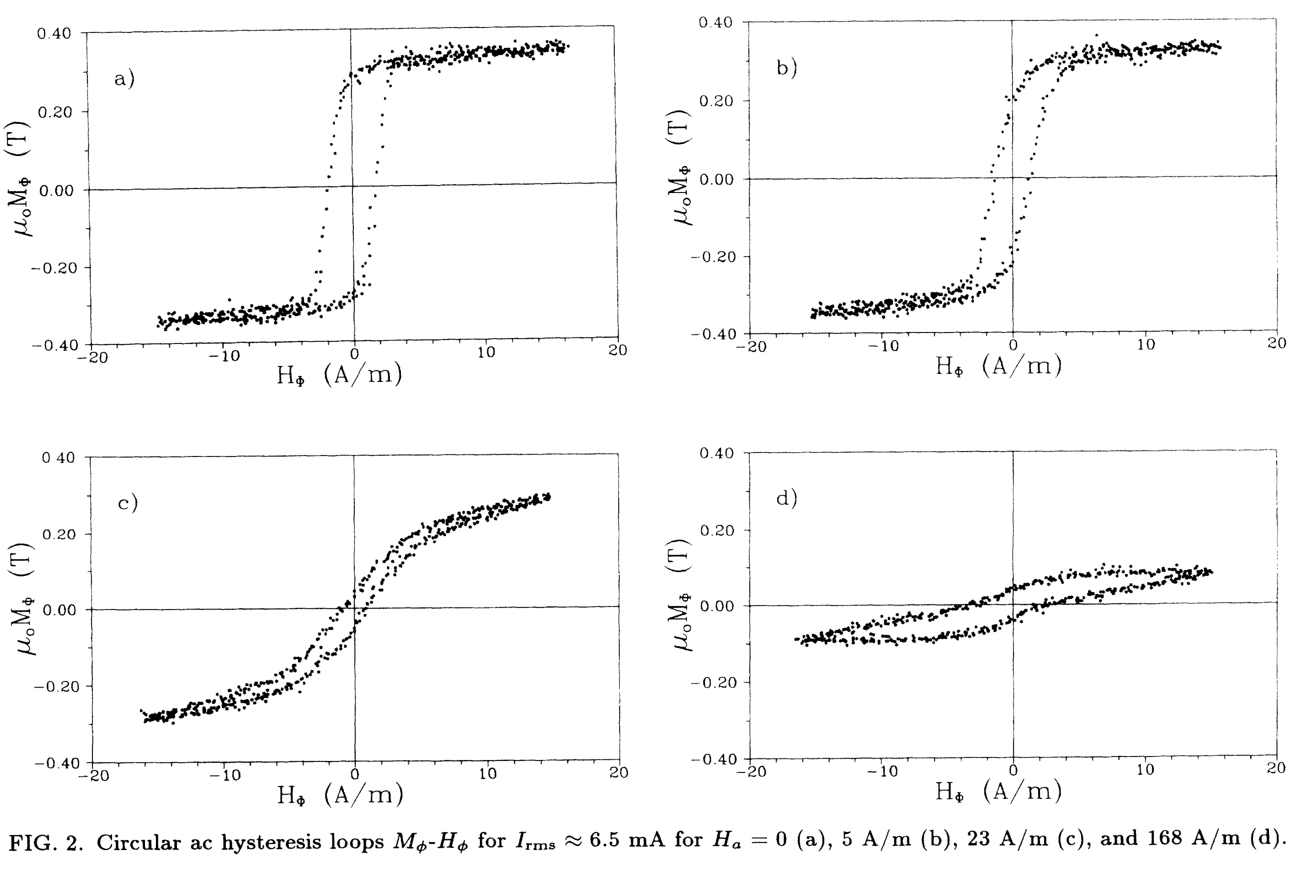

FIG. 2. Circular ac hysteresis loops M_ϕ-H_ϕ for $I_{\mathrm{rms}} \approx 6.5$ mA for $H_a = 0$ (a), 5 A/m (b), 23 A/m (c), and 168 A/m (d).

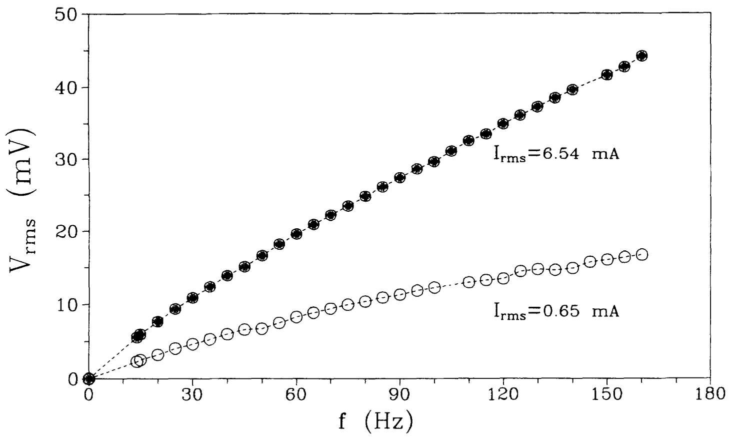

FIG. 3. V_{rms} as a function of frequency f when $I_{\mathrm{rms}} = 0.65$ and 6.54 mA.

with small λ_s. Thus, both axial and circular hysteresis loops will approach becoming rectangular with larger coercivity. The small I_{rms} corresponds to a maximum circular field $H_{\phi\max}$, significantly smaller than the circular coercivity $H_{\phi c}$. In this case, the circular susceptibility χ_ϕ is defined in the almost reversible initial range of the magnetization curve, with a very small maximum circular magnetization $M_{\phi\max}$, so that V_{rms} is very small. On the contrary, at large I_{rms} we have $H_{\phi\max} > H_{\phi c}$ and a large χ_ϕ close to that without twist; so V_{rms} vs H_a has a similar behavior to the other cases.

To illustrate the circular magnetization behavior, we show in Fig. 2 some hysteresis loops at different values of H_a. The measuring conditions are $I_{\mathrm{rms}} \approx 6.5$ mA, without applied stresses, and $f = 82$ Hz. The circular magnetization M_ϕ was obtained from the inductive voltage V using

$$V = \mu_0 r l d M_\phi / dt. \tag{1}$$

The average circular field is defined as

$$H_\phi = I/4\pi r. \tag{2}$$

We observe from Fig. 2 that increasing H_a decreases $M_{\phi\max}$ by a factor of around 4, consistent with the I_{rms} data shown in Fig. 1(b). $H_{\phi c}$ is around 2 A/m for all cases. This value is the same as that for axial coercivity. If domain wall depinning is the mechanism of coercivity, and the wall energy is proportional to stress anisotropy, then the same axial and circular coercivity implies an overall uniform stress distribution between the axial and circular directions.

If $H_{\phi\max}$ corresponding to a given I_{rms} reaches $H_{\phi c}$, χ_ϕ will be the largest. This situation occurs at $I_{\mathrm{rms}} \approx 0.7$ mA, and this is consistent with the roughly 2.5 times larger $V_{\mathrm{rms}}/I_{\mathrm{rms}}$ for $I_{\mathrm{rms}} = 0.65$ mA than for $I_{\mathrm{rms}} = 6.54$ mA, as displayed in Figs. 1(a) and 1(b) for the data without stresses. The $H_{\phi c}$ for twisted wire should be significantly larger than the low-I_{rms} maximum circular magnetization, so that χ_ϕ and thus V_{rms} are degraded.

In the above we have shown results measured at 82 Hz. The reactance of the wire should increase with increasing frequency f, and if at a certain high f it reaches a value close to the resistance of the wire, R, a GMZ will appear. The results shown in Refs. 4 and 15 belong to this case. The frequency dependence of V_{rms} for both values of I_{rms} is shown in Fig. 3. The behavior is roughly linear with a downturn. Assuming R to be constant and neglecting the magnetic loss angle and the air inductance, we obtain the maximum relative change in impedance

$$(\mathrm{MZ})_{\max} = \frac{Z_{\max}}{Z_{\min}} - 1 = \sqrt{1 + \left(\frac{\pi\mu_0 r^2 \chi_{\phi\max} f}{2\rho}\right)^2} - 1, \tag{3}$$

where ρ is the resistivity of the wire. From Eq. (3) we see that $(\mathrm{MZ})_{\max}$ increases with increasing r and $\chi_{\phi\max}$ and decreasing ρ. Thus, for our amorphous wire, which has a high ρ ($\approx 1.2 \times 10^{-6}\ \Omega\,\mathrm{m}$) and a small r, the origin of the GMZ at high f is its large $\chi_{\phi\max}$. However, the high $\chi_{\phi\max}$ at high f requires a large ρ and small r, owing to the eddy-current losses. It is interesting to find the key factors for achieving as large a $(\mathrm{MZ})_{\max}$ as possible.

Following the experimental conditions in Ref. 4, we assume $f = 100$ kHz for our wire, and calculate $(\mathrm{MZ})_{\max}$ using Eq. (3) and find that for having $(\mathrm{MZ})_{\max} = 27\%$, $\chi_{\phi\max}$ should be 820. This value is reasonable considering the eddy-current effects at high frequencies; the maximum $\chi_{\phi\max}$ at 82 Hz is close to 10^5, estimated from Fig. 2(a). Therefore, the ac GMR appearing in the literature is actually a GMZ. The $(\mathrm{MZ})_{\max}$ can be increased by increasing $\chi_{\phi\max}$. If $\chi_{\phi\max} = 1000$ and 1600, $(\mathrm{MZ})_{\max}$ is calculated to be 40% and 100%, respectively.

In conclusion, we have reported data concerning the variations of inductive voltage across an amorphous nonmagnetostrictive wire when it is subjected to external agents such as dc magnetic field and mechanical stresses. The change of voltage is associated with the modification of circular magnetic susceptibility. At high frequencies the reactance of the wire at low fields can be as large as its resistance, so that a giant magnetoimpedance is expected. Such an effect can be useful in a number of technological applications for magnetic sensors and magnetic recording.

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