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Hysteretic giant magnetoimpedance effect analyzed by first-order reversal curves

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ABSTRACT

We applied the first-order reversal curve method to hysteretic giant magnetoimpedance (GMI) of soft magnetic amorphous ribbons with a well-defined transversal domain structure and quasi-anhysteretic magnetization behavior. In opposition to major curve, it gives access to the distribution of local irreversible changes of the transverse permeability, which undergo a gradual transition. Results show that hysteretic GMI effect consists of three distinct regimes depending on the applied field. An interlinked hysteron/anti-hysteron model is proposed to analyze the obtained results, which allows one to follow the influence of frequency and anisotropy upon the irreversible switches probed by GMI.

1. Introduction

The giant magnetoimpedance (GMI) effect consists of a drastic change (up to hundreds of percent) of the electrical impedance Z of a magnetically soft conductor upon application of an external magnetic field H. It is related to variations of the effective magnetic permeability μ, which is strongly affected by the external magnetic field and the frequency f of the ac driving current i. In magnetic metals, the variation of μ as a function of H and f governs the change of the penetration depth δ of the electromagnetic fields through the sample, producing the GMI effect. Although it was first observed around seven decades ago [1], its intense investigation started only in 1994 [2]. This "rediscovery" of GMI in amorphous soft magnetic alloys attracted much attention of scientific community owing to its potential application in ultra-sensitive magnetic sensors and reading heads, as well as an investigation tool for material parameters [3]. While theoretical models of the transverse permeability μ_t adequately explain the GMI behavior in a broad range of H and f [4–6], improvements have been done to include unsaturated behavior (H less than the anisotropy field H_k) [7]. One notable example is the hysteretic behavior of the GMI curve, which has been observed in several types of systems, mainly ribbons [8–11] and microwires [9,12,13] with transverse or circumferential anisotropy and for relatively low frequencies (tens of MHz and below). It was attributed to various physical phenomenon, predominantly irreversible domain wall motion and axial magnetization switches. This effect is of high technological relevance, especially for applications of GMI at low fields [14]. The hysteresis can be detrimental for applications such as magnetic sensors, while others can take advantage of it, such as memories. However, the previous studies on the subject were limited to GMI and magnetization major curves, which represent the whole system global behavior.

On the other hand, the first-order reversal curve (FORC) method is one of the most powerful tools to investigate the origins and to characterize the materials general hysteretic behavior [15]. Since 1985 it has been successfully applied to probe the magnetization (M) hysteresis in several systems [16–19], but its mathematical nature allows a more general use [15]. The FORC method has already been successfully used to investigate the hysteretic behavior of other parameters: ferroelectricity [20], pressure [21] and giant magnetoresistance (GMR) [22]. The main advantage over major hysteresis curves is that it gives the distribution of local properties, instead of average, which can be crucial when dealing with non-uniform systems. Thereby, the FORC method must be seen as a powerful experimental tool that can be used to probe the hysteretic behavior of any system that respects the wipe-out and congruency conditions [15].

In this article, the measurement procedure of the FORC method was applied to the electrical impedance response as a function of the longitudinal external field of FeCoSiB amorphous ribbons with well-defined transversal domain structure. While their GMI responses exhibit hysteresis at low field, the magnetization presents a quasi-reversible behavior. The FORC results represent the distribution of each local irreversible switch, thereby dissecting the GMI hysteresis. We conceived a new type of hysteron to adapt the traditional FORC analysis to the particular type of hysteresis

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exhibited by the GMI signal, which describes an even function. This new analysis is thought to be easily adaptable to similar functions, like magnetoresistance and magnetostriction, among others. The novel established FORC procedure for GMI signal (called GMI-FORC) allows the investigation of the effects of different parameters (current amplitude and frequency, ribbon characteristics, etc.) on the hysteretic process, and so their specific repercussions on the ribbon magnetic structure.

2. Ribbons characterization

Amorphous ribbons of $(Fe_xCo_{1-x})_{70}Si_{12}B_{18}$ ($x=0.045$–0.050), 22 μm thick, were prepared by melt spinning technique. A proper annealing treatment, described in [23], induced magnetostriction, which constant depends on the Fe/Co ratio. It results of a rather well-defined uniaxial anisotropy with easy axis perpendicular to the ribbon axis, as confirmed by a representative magnetic optical Kerr effect (MOKE) image (Fig. 1). The major magnetization curve as a function of a longitudinal applied field, measured with a high-precision AC induction magnetometer [24], shows a mostly reversible behavior, with a small detectable hysteresis, as expected owing to the transversal anisotropy (Fig. 2).

In contrast, the GMI curve ($i=1$ mA, $f=500$ kHz, $\delta\approx 3$ μm) as a function of the longitudinal static applied field reveals a different behavior. In addition to the two typical peaks associated with the anisotropy field clearly visible around $H=\pm 6$ Oe, it exhibits an important hysteretic region at low field ($H=\pm 4.5$ Oe), which is symmetric around the origin (Fig. 2). Magnetization detects longitudinal irreversibility while GMI probes the irreversibility of the transverse permeability μ_t. The combination of both may lead to better understand the local mechanisms governing the magnetization of soft magnetic amorphous ribbons.

3. FORC method

The FORC method is based on the classical Preisach model. The global behavior of the hysteresis is associated with a collection of single square irreversible curves, called mathematical hysterons and representing the hysteresis operators [15]. The method consists of the measurement of increasing minor hysteresis curves starting from different input values, called reversal points (H_r for field-driven hysteresis), and reaching the positive saturation. The mathematical hysterons distribution, the so-called FORC distribution function, $\rho(H, H_r)$, is obtained through the calculation of a second-order mixed derivative of the output variable with respect to the reversal and measuring field values [15]. In the present case, the impedance, which is the output variable, was separated into its real (R) and imaginary (X) parts before the calculation, leading to two distinct FORC distributions (for $H > H_r$):

$$\rho_R(H,H_r) = -\frac{1}{2}\frac{\partial^2 R(H,H_r)}{\partial H \partial H_r} \quad (1)$$

$$\rho_X(H,H_r) = -\frac{1}{2}\frac{\partial^2 X(H,H_r)}{\partial H \partial H_r} \quad (2)$$

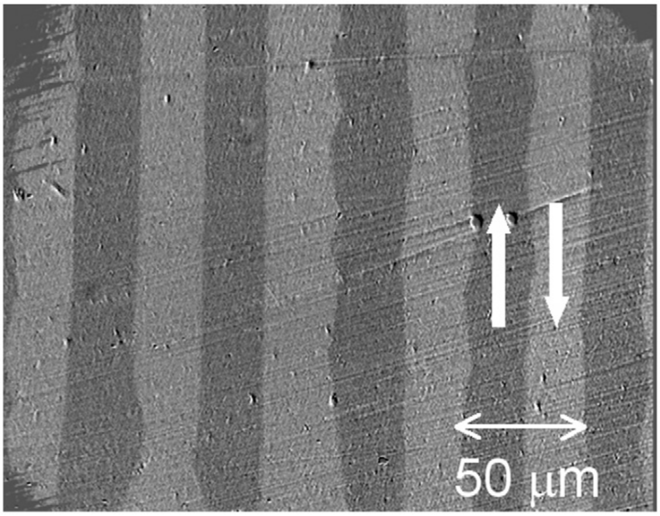

Fig. 1. Top-view MOKE image of the studied FeCoSiB ribbon. The alternation of dark and clear domains signifies antiparallel perpendicular domains, resulting of the well-defined transversal magnetic anisotropy. The arrows indicate the magnetization direction.

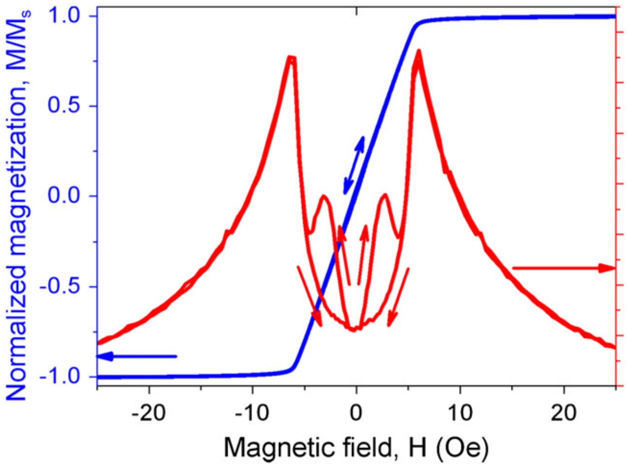

Fig. 2. FeCoSiB ribbon ($x=0.045$) typical major curves of magnetization and GMI signal ($f=500$ kHz, $i=1$ mA, $\delta\approx 3$ μm) under a longitudinal applied field.

Compared to the major hysteresis curve, which gives the average behavior of the hysteretic operators, it presents the advantage to yield the function distribution of those. For complex systems, hysteretic phenomena can not be directly modeled as mathematical hysterons. In such cases, an essential step consists of modeling an assembly of mathematical hysterons that adequately describes the behavior of each hysteretic process occurring [25]. For GMI-FORC, we elaborated a dual-hysteron model that represents the elementary irreversible behavior of the GMI (see Section 4.2). For further interpretation of the FORC diagram, one needs to correctly identify the physical meaning of those dual-hysterons.

4. GMI-FORC

4.1. FORCs

The measured FORC curves (GMI-FORCs) were obtained by measuring the impedance, at a fixed frequency, when H was varied from H_r back to positive saturation (Fig. 3(a), thin colored lines). They were confined in this region, because the reversible behavior occurring at higher field yields a null FORC distribution. In order to avoid artifacts on the FORC distribution and visualize better the irreversible variations, we subtracted the lowest major curve (Fig. 3(a), thick black line) from each FORCs before the FORC distribution calculation.

The resulting FORCs (Fig. 3(b), thin colored lines) are not confined within the two paths described by the major curve, passing through the two hysteretic areas as well as outside them. Therefore, the μ_t irreversibility of the entire ribbon is not constituted of only