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Characterizing magnetic interactions in Ni nanowires by FORC analysis

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Abstract

Polycrystalline Ni nanowires with different diameters were electrodeposited in nanoporous anodized alumina membranes. First-Order Reversal Curves (FORCs) were measured and FORC distributions were calculated. They clearly showed an asymmetric behavior with a strong maximum at negative interaction fields, evidencing the dominant demagnetizing interactions which depend on the geometry of the nanowires.

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Keywords: Magnetic nanowire; FORC; Demagnetization process; Electrodeposition

1. Introduction

Self-organized arrays of ferromagnetic nanowires show potential feasibility for applications in perpendicular magnetic recording media and high-sensitivity magnetic sensors [1], and are well suited for both experimental and theoretical study of magnetism at nanoscale [1–4]. These systems can be easily synthesized through the method of two-step anodization [5] and subsequent chemical electrodeposition [2,3].

One phenomenological approach that has been topic of renewed interest in magnetic systems is the First-Order Reversal Curves (FORC) analysis [6–11]. FORCs can be experimentally obtained as follows: (a) first, one has to saturate the sample with a field H_{max}; (b) then, set the field H to a return value $H_r < H_{max}$; (c) then, increase H back to H_{max}, measuring the magnetization; and (d) and repeat steps (b) and (c) for decreasing values of H_r, while $H_r \geqslant -H_{max}$.

The FORC distribution is, then, defined by $\rho(H_r, H) \equiv -0.5\{\partial^2 M(H_r, H)/\partial H_r \partial H\}$ and performed on the dataset of the measured FORCs. The FORC diagram is a contour plot of ρ on a 45° rotated coordinate system $\{H_c = (H - H_r)/2,\quad H_b = (H + H_r)/2\}$. In these coordinates, ρ can be compared to the statistical distribution of particles from the Preisach model [12], which describes the field-induced reversal of an ensemble of single-domain particles.

Thus, the FORC diagram provides a detailed characterization of the hysteretic response of a system because it evidences dominant magnetic interactions, magnetic after-effects and the annihilation of memory during the demagnetization process.

In this work, a set of samples of Ni nanowires grown in the nanoporous anodized alumina membranes were magnetically characterized by FORC analysis.

2. Experimental details

Thin (0.2 mm) Al foils with 99.997% purity were pretreated in vacuum at 600 °C for 2 h; washed in acetone; electropolished in a $H_2SO_4 + H_3PO_4 + H_2O$ solution; etched in a 3 M NaOH solution and rinsed in deionized water. Later, the foils were anodized in a constant voltage cell containing an aqueous solution of 0.3 M oxalic acid ($H_2C_2O_4$), at 4 °C, using a graphite electrode as cathode. The first anodization was carried out for 1 h and the second for 40 min. Several samples were prepared with anodization voltage V_{an} varying between 15 and 30 V. The electrodepositions were carried out in a solution of 0.1 M $NiSO_4 \cdot 6H_2O + 45\,g/L\,H_3BO_3$, at 55 °C, for 2 min, under 20 V, at 100 Hz.

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The structural characterization was done by Scanning Electron Microscopy (SEM) and X-ray Diffractometry (XRD), with Cu K_α radiation. The magnetic characterization was accomplished at 300 K in a 7T-SQUID, with magnetic field applied perpendicularly to the membrane surface.

3. Structural and magnetic characterization

SEM images of the samples were obtained and treated in a suitable image processing software, from where we calculated the mean diameter d_m, the mean interpore distance D_{int} and the density of pores. A linear dependence of d_m and D_{int} with V_{an} was observed, with d_m between 30 and 90 nm and D_{int} between 40 and 110 nm, in agreement with the literature [13,14]. The mean density of pores varies between 10^9 and 10^{10} pores/cm^2. The shape of the pores also varies with V_{an}. Samples made at 30 and 40 V have a more regularly oriented hcp patterns. Below $V_{an} = 30$ V, the pore arrays are predominantly random, whereas above 40 V the pores tend to deform. It is well known that the regularity of the pore array depends on voltage and duration of the first anodization [15–17] and that for high V_{an} the pores tend to diverge from the circular shape [18]. On the other hand, the length of the pores depends solely on the duration of the second anodization [13]. We estimate that our samples have lengths between 5 and 15 μm, yielding an aspect ratio greater than 50.

The XRD patterns confirm the presence of polycrystalline Ni. The (1 1 1) peak of Ni was not detected due to its coincidence with the strong (2 0 0) peak of Al. The grain sizes of Ni were calculated for each crystallographic direction and they were seen to increase with d_m, in the range of 10–22 nm, indicating that the geometry of the pores regulates the grain size of Ni. In this range, the crystallites must be exchanged-coupled single-domain particles, with random orientation of easy axes [2]. Such a magnetic structure can allow non-uniform modes of magnetization reversal [19,20].

The shape uniaxial anisotropy in our samples was confirmed by measuring hysteresis loops in the directions perpendicular and parallel to the wires. An outstanding increase of coercive field H_C and remanence ($M_R > 0.5M_S$), in comparison to bulk Ni, was observed. It is in accordance with Ref. [19]. To obtain the FORC distributions, approximately 20 FORCs with $H_{max} = 3$ kOe were measured for each sample (see Fig. 1a). The FORC distributions were calculated by the method described by Heslop and Muxworthy [11], applying the "extended" FORC definition [7], normalized by the saturation magnetization M_S of each sample and plotted in the $\{H_c, H_b\}$ coordinates. Fig. 2b displays typical results for the sample with $d_m = 38$ nm.

4. Results and discussion

In the classical Preisach model, a distribution of non-interacting single-domain particles is considered, where

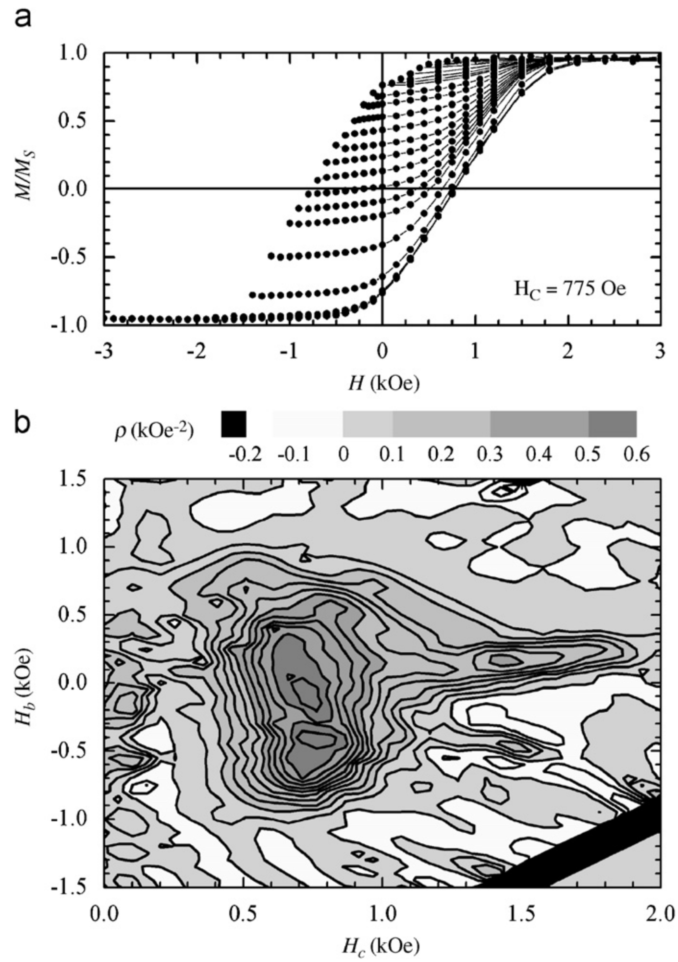

Fig. 1. (a) FORCs and (b) FORC diagram for the sample with $d_m = 38$ nm.

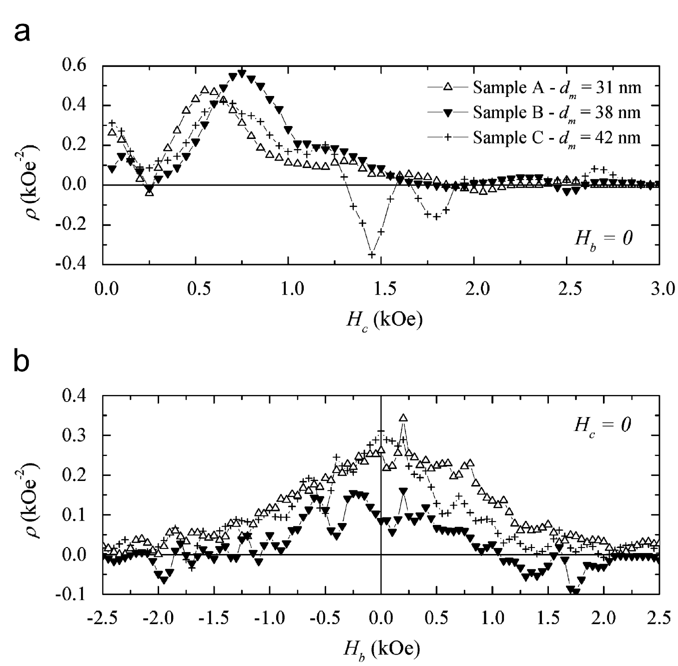

Fig. 2. FORC distribution of all samples at (a) $H_b = 0$ and (b) $H_c = 0$.