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Angular dependence of the coercivity in arrays of ferromagnetic nanowires

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ABSTRACT

We present a new magnetic model for polycrystalline nanowires arrays in porous anodic aluminum oxide. The principal consideration here is the crystalline structure and the morphology of the wires and them the dipolar interactions between the crystals into the wire. Other aspect here is the direct calculation of the dipolar energy for the interaction of one wire with the others in the array. The free energy density was formulated for polycrystalline nanowires arrays in order to determinate the anisotropy effective field. It was using the microstructure study by scanning and transmission electron microscopy for the estimation of the real structure of the wires. After the structural analysis we used the angular dependences for the coercivity field and for the remnant magnetization to determine the properties of the wires. All analysis were made by the theory treatment proposed by Stoner and Wohlfarth.

1. Introduction

Arrays of magnetic nanowires are technological and academic important due to their properties and applications [1–6]. The most popular technique used to obtain these systems is the electrochemical route in anodic aluminum oxide [7,8] because we can produce ordered arrays into the membrane pores [8–12]. Many research groups investigated the magnetic interactions in these systems [13–16]. In some works were proposed different modes for the magnetization reversal [15–22]. Stoner and Wohlfarth [17] investigated the reversion process for the magnetization in non-interacting particles using the coherent mode. Landeros et al. [18] observed the predominance of the coherent mode when we have short particles. Padrón et al. [16] showed a way for express the magnetic free energy in polycrystalline nanowires. In this article they proposed that wires are a sequence of identical spheroids along the wire axis and the particles only feel dipolar interactions from the others. Encinas-Oropesa et al. [23] using a mean field approximation had proposed the interactions between nanowires on the array. They expressed the magnetic anisotropy field as a function of the packing factor of the wires in the array, *P*. Some models had considered the magneto-crystalline energy according to the situation [5,17,20].

Some articles explained how the moments are reverted with the external magnetic field decreases. In other hand they have not a mathematical equation describing the angular dependence for the coercivity in the system. In this paper we present a simples and realistic model to resolve discrepancies in the literature. With our equations we can fit the experimental results for all experimental data published in polycrystalline nanowires with nanometric diameter. We can explain the results based on the microstructural properties of the nanowires. Our method is a way for determining the magnetic anisotropy field from the angular dependence of the coercivity and the remanence.

2. Experiment

For the preparation of polycrystalline nanowire arrays we used membranes of anodic aluminum oxide (AAO) as template and electrodeposited the desired material (nickel) within the cylindrical pores. AAO was obtained by electrochemical oxidation of aluminum plates Aldrich 99.9999%, with a voltage of 20 V in aqueous acid solutions with the same concentrations described in [16]. The experiments where using a Potentiostat Model IVIUMSTAT.XRe. As the result we have cylindrical pores diameter of 25 nm as shown in Fig. 1(a). The nanowires were fabricated by electroplating with AC potential of 17 V rms (Fig. 1(b)). The deposited wires have an average length of 6 mA. We used a solution of 2.0 M NaOH, so we removed the wires from the pores of the membrane and analyzed the crystalline by transmission electron microscopy, Fig. 1(c). The samples were fabricated in membranes

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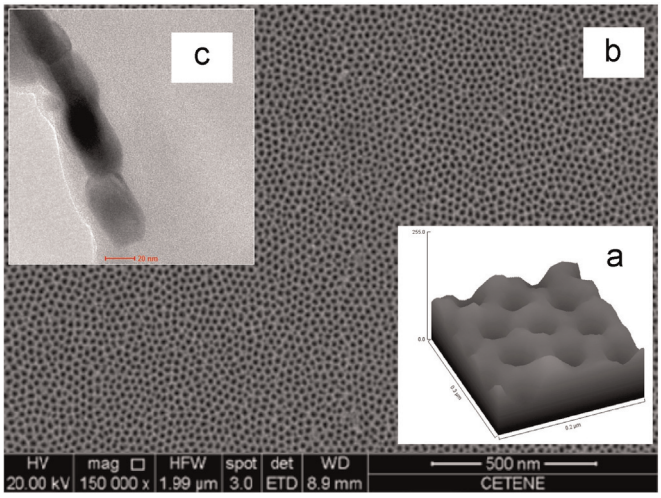

Fig. 1. (a) Contrast Plot for a SEM image showing the packing of the wires. (b) SEM image for the membrane after electro-deposition. (c) TEM image for a wire showing the polycrystalline nanowires and the dimensions for the ellipsoids.

with pores radio $R=12.5$ nm and the center to center pores distance 52 nm. Ni nanowires where deposited according to the experimental method exposed here and have 6 µm. We made two samples, one as deposited (*NiSTT*) and the other with thermal treatment (*NiCTT*) in 300 °C and Argon atmosphere.

Measurements of magnetization curves at room temperature were made on the samples (with and without heat treatment) to that used a Microsense Vibrating Sample Magnetometer (VSM). Also made the measurements of Henkel plots [24,25] and calculated curves Deltha-m [26].

3. Model

The expression proposed by Padrón et al. [16] for the density of magnetic free energy in a linear chain of interacting ellipsoids with an applied external field (H) is

$$E_{wire} = \pi M_S^2\left[\left(\frac{3V_e k_n}{\pi r^3}\right) + \left(1 - 3N_{//}\right)\right]\sin^2(\varphi - \theta_H) - M_S H\cos(\varphi). \quad (1)$$

Here the first term is the energy density of dipolar interaction between ellipsoids, the second refers is the energy density self-demagnetizing of each ellipsoid. M_S is the saturation for the magnetization, r is the center to center ellipsoid distance, $H_C = \left|H_n^f\right| = (H_A/1+\xi^\alpha)$ is the self-demagnetizing factor for an individual ellipsoid along the chain [27], V_e the ellipsoid volume, $|1+\xi^\alpha| = 1+\xi^\alpha$ and $\varphi = \theta_M + \theta_H$. In this equation, n is the number of ellipsoids in the chain, θ_M is the angle between the chain axis and the magnetic moments and θ_H is the angle between the magnetic field and the chain axis.

According to the mean field approximation from Encinas-Oropesa [23], we can write the inter-chains (inter-wires) dipolar interaction as $E_{int} = -3\pi M_S^2 P\sin^2(\varphi - \theta_H)$. In our experiment the magneto-crystalline energy is lower than the other contributions, that is why including the inter-wire interactions we can write the total energy as

$$\eta = \frac{1}{2}\sin^2(\varphi - \theta_H) - f\cos(\varphi) \quad (2)$$

$\eta = E_{array}/K_{eff}$, $f = M_S H/K_{eff}$ and $K_{eff} = 2\pi M_S^2\left[1 + 3\left(V_e k_n/\pi r^3 - N_{//} - P\right)\right]$. We can see that the angular dependence for η is according to the Stoner–Wohlfarth model [17]. For this reason we use the same treatment to find the nucleation field in the coherent mode for our interacting particles. For the critical values we have $d\eta/d\varphi|_{\varphi=\varphi_0} = 0$ and $d^2\eta/d\varphi^2\Big|_{\varphi=\varphi_0} \geq 0$, in order to find the energy extremes. We have $\varphi = \theta_{M,0} + \theta_H$ and $\theta_{M,0}$ for the equilibrium angles and θ_H from the experiment, measured from the wire axis. With this arguments find the same equation found by Stoner and Wohlfarth [17], $f|_{\varphi=\varphi_0} = -1/\left(\cos^{2/3}(\theta_H) + \sin^{2/3}(\theta_H)\right)^{3/2} = 1/g_0$. This expression for g_0 define the nucleation field for our arrays of polycrystalline wires, $H_n^i = H_A/g_0$, with $H_A = K_{eff}/M_S$.

We know that the coercivity is lower than the nucleation field, $\left|H_n^i\right| \geq H_C$ and we can restrict $0 \leq \theta_H \leq \pi/2$, due to the symmetry around $\theta_H = 0$ and $\theta_H = \pi/2$. For the orientation $\theta_H = 0$, $H_C(\theta_H = 0) = \left|H_n^i(\theta_H = 0)\right| = \left|H_A/g_0(\theta_H = 0)\right| = H_A$. Now we propose $H_C(\theta_H) = \left|H_A/y(\theta_H)\right|$ with $\left|y(\theta_H = 0)\right| = \left|g_0(\theta_H = 0)\right| = 1$ and $y(\theta_H) = 1 + \xi^\alpha$ where $\xi = \theta_H/rad$. The $\alpha > 0$ parameter is experimental and is related with the interactions of the wires and it atomic ordering. An expression for this parameter is $\alpha = \left|\left[1/\ln\left(\xi\left(\theta_H^f\right)\right)\right]\left[\ln\left(\left(H_C\left(\theta_H^i\right) - H_C\left(\theta_H^f\right)\right)/H_C\left(\theta_H^f\right)\right)\right]\right|$. Where θ_H^i and θ_H^f are the extreme fields for the angular interval. In this way for any angle, the nucleation field is $\left|H_n^f\right| = \left|H_A/(1+\xi^\alpha)\right| = H_C$. According to the situation $|1+\xi^\alpha| = 1+\xi^\alpha$then we have for $0 \leq \theta_H \leq \pi/2$

$$H_C = \left|H_n^f\right| = \frac{H_A}{1+\xi^\alpha}. \quad (3)$$

It is important to note that our expression for α is empirical and not a consequence of the Stoner–Wohlfarth theory.

For the remanent magnetization we use the same condition for an null applied external field,

$$E_{array} = \left[\pi M_S^2\left(\frac{3V_e k_n}{\pi r^3} + 1 - 3N_{//} - 3P\right)\right]\sin^2(\varphi - \theta_H) - 4\pi M_r M_S\cos(\varphi), \quad (4)$$

and the non-dimensional energy is,

$$\eta = \frac{1}{2}\sin^2(\varphi - \theta_H) - \gamma\cos(\varphi) \quad (5)$$

where, $\gamma = 4\pi(m_r M_S)/H_A$ and $m_r = M_r/M_S$. Using the critical values defined by Stoner and Wohlfarth [17], $d\eta/d\varphi|_{\varphi=\varphi_0} = 0$ e $d^2\eta/d\varphi^2\Big|_{\varphi=\varphi_0} \geq 0$, we find $\gamma|_{\varphi=\varphi_0} = -1/\left(\cos^{2/3}(\theta_H) + \sin^{2/3}(\theta_H)\right)^{3/2} = 1/g_0$. The reduced remanence for the critical values is, $m_r^i = H_r/g_0$ and $H_r = H_A/(4\pi M_S)$. Now we have $m_r(\theta_H = 0) = \left|m_r^i(\theta_H = 0)\right| = \left|H_r^0/g_0(\theta_H = 0)\right| = \left|H_r^0\right|$,

Using the same conditions proposed for the coercivity we have for the remanence, $m_r = |H_r|/1+\xi^\alpha$ and α can be determined too by the equation, $\alpha = \left|\left[1/\ln\left(\xi\left(\theta_H^f\right)\right)\right]\left[\ln\left(\left(m_r\left(\theta_H^i\right) - m_r\left(\theta_H^f\right)\right)/m_r\left(\theta_H^i\right)\right)\right]\right|$. Here we made the analyses for $\left|H_r\right|$, $\left|H_r\right| = H_r$ if $m_r(\theta_H = 0)$ is maximum or $\left|H_r\right| = -H_r$ if $m_r(\theta_H = 0)$ is minimum [28]. Then

$$m_r = \frac{H_r}{1+\xi^\alpha} \quad (6)$$