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Micromagnetic simulation and the angular dependence of coercivity and remanence for array of polycrystalline nickel nanowires

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ABSTRACT

We present here our experimental results for the preparation and characterization of nanowires of nickel and the analysis of the angular dependence of coercivity and remanence using experimental data and micromagnetic simulation. The fabrication was made by using aluminum oxide membranes as templates and deposited nickel by an electrochemical route. The magnetic measurements showed that coercivity and remanence are dependent of the angle of application of the external magnetic field. Our results are different than that expected for the coherent, vortex and transversal modes of the reversion for the magnetic moments. According to the transmission electron microscopy analysis we can see that our nanowires have not a perfect cylindrical format. That is why we have used the ellipsoids chain model for better understanding the real structure of wires and its relation with the magnetic behavior. In order to generate theoretical results for this configuration we have made micromagnetic simulation using Nmag code. Our numerical results for the realistic distances are in correspondence with the magnetic measurements and we can see that there are contradictions if we assume the transverse reversal mode. Then, we can conclude that structure of nanowires should be taken into account to understand the discrepancies reported in the literature for the reversion mechanism in arrays of nickel nanowires.

1. Introduction

Arrays of magnetic nanowires have technological and academic importance 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 membranes [7,8] because we can produce ordered arrays into the pores [8–12]. Many research groups have investigated the magnetic interactions in these systems [13–16]. In some works were proposed different modes for the reversion of the magnetization [15–29]. Stoner and Wohlfarth [17] investigated the reversion process for the magnetization in non-interacting particles using the coherent mode. Landeros et al. [18]. have observed the predominance of the coherent mode for nanowires constituted by short particles. Hernández et al [16]. showed an alternative for express the magnetic free energy in polycrystalline nanowires. In this work the proposition was that the wires are a chain of identical ellipsoids. The chain of ellipsoids extends along the wire and ellipsoidal particles experience only dipolar interactions. Encinas-Oropesa et al [23]. using a mean field approximation proposed the interactions between nanowires on the array. They expressed the effective magnetic field as a function of the packing factor of the wires in the array, *P*. Some models take into account the magnetocrystalline energy depending on the material [5,17,20]. Many studies have attempted to establish a phase diagram for the reversion of the magnetic moments. In other hand, there is not a definitive mathematical equation describing the angular dependence for the coercivity and remanence in these systems. It is evident that the microstructure is critical to study this problem and every model will enter the real characteristics of nanowires. The aim of this paper is to show that the understanding of the magnetic properties of nanowires is an open problem. Also that structure is fundamental to study the reversion process of the magnetic moments. For this purpose we present our experimental results for nickel nanowires arrays and based on the electron microscopy results we've used a model of ellipsoid chains for generate the magnetic response by micromagnetic simulation. Our results show a great correspondence of the experimental data and the numerical calculation.

2. Experiment

The sample preparation was made using membranes of anodic

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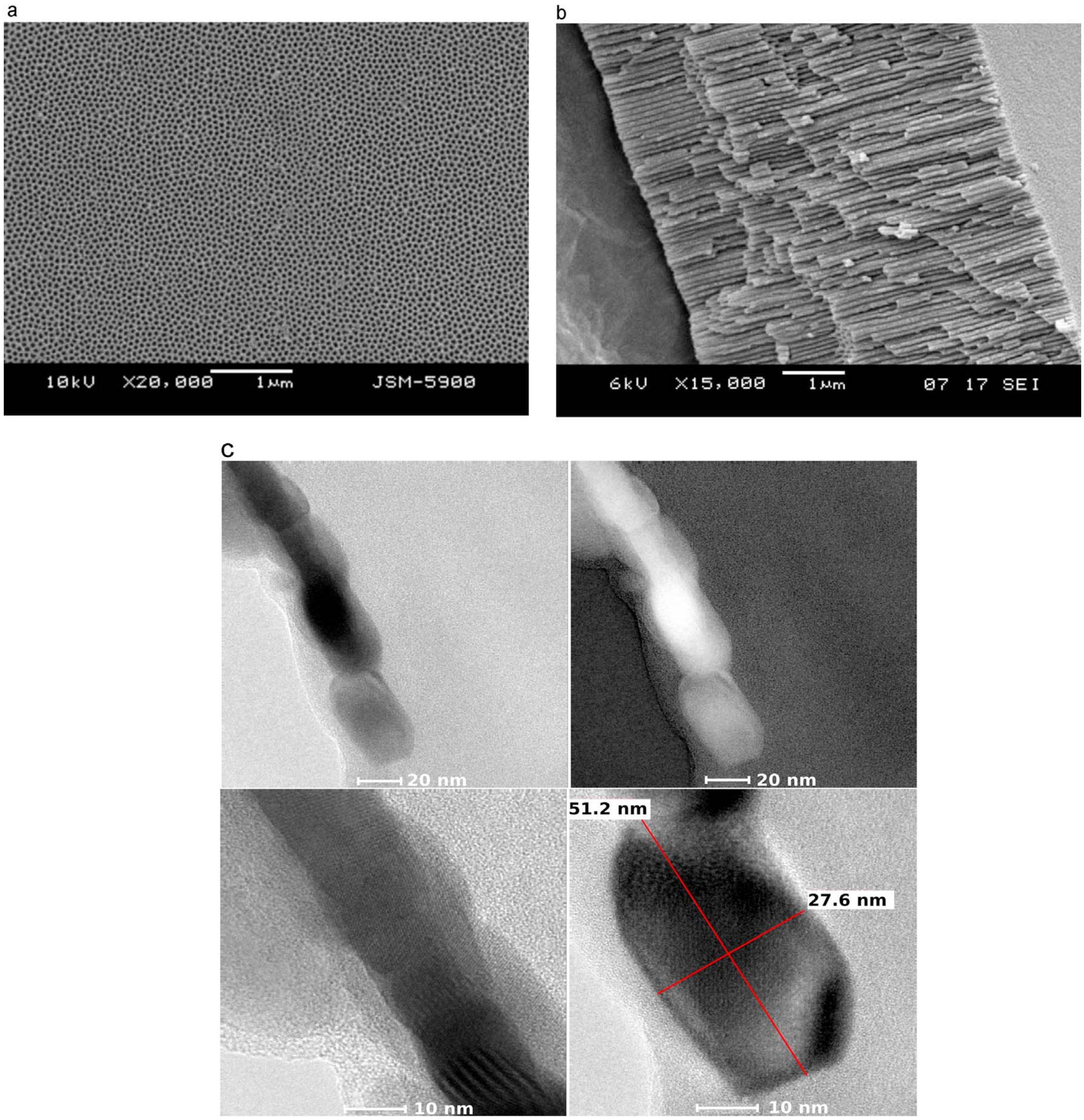

Fig. 1. (a) Top view of membranes used for electrodepositing nickel nanowires. (b) Lateral view of nanopores showing the linear channel appropriated for the desired format of nanowires. (c) TEM images show the nanowires microstructure. We have a polycrystalline nanowire similar to an ellipsoid chain. Bright-field shows the ellipsoids constituting the nanowires and Dark-field image proves that nanowires are crystalline. HRTEM by the phase contrast show the plane family confirming the Ni nanocrystals.

aluminum oxide (AAO) as a template and then the desired material (nickel) was electrodeposited within the cylindrical pores. AAO membranes were obtained by electrochemical oxidation of aluminum plates Aldrich 99.9999%, with voltage of 20 V in aqueous acid solutions with the same concentrations described in some works [6]. The experiments where performed using a Potentiostat Model IVIUMSTAT.XRe. We have obtained cylindrical pores about 25 nm in diameter, measured by SEM. Nanowires were fabricated by the electroplating in AC potential of 17 V rms. The deposited wires have an average length of 600 nm, measured by SEM. The nickel nanowires were fabricated into membranes with pores radius of R =12.5 nm and the center-to-center pores distance of 42 nm, measured by SEM. We made two samples of Ni: the as deposited, *NiSTT* and the heat-treated in 300 °C on Argon atmosphere, *NiCTT*. Magnetization curves were performed with the field in different orientations and we have registered the angular dependence of coercivity and remanence. Magnetic measurements were performed in a vibrating sample magnetometer (VSM) fabricated by Microsense. Transmission electron microscopy images were registered in a Tecnai2G 200 kV and scanning electron microscopy in a Quanta FEG both fabricated by FEI Company.

3. Results and discussion

The structure of nanowires had been analyzed using scanning and transmission electron microscopy (SEM and TEM) as showed in Fig. 1. The used membranes for the deposition are presented in Fig. 1a and b for and we can see the local hexagonal arrangement of pores. The pores are linear channels and have dimensions useful for evaluate the magnetic properties of nickel nanowires. Fig. 1c presents a structural important result obtained by TEM, we can see in the bright-field images that our nanowires are constituted by ellipsoidal nanoparticles. This format is due to the nitrates used as the precursors for electrodepositing the material. The dark-field images show that these nanoparticles are crystalline and by HRTEM and phase contrast we can see the crystalline planes for nickel. In the same images we measured the aspect ratio for the principal axes of the ellipsoidal nanoparticles. Thus we can conclude for this set of pictures that our nanowires are constituted by a chain of nano-ellipsoids. This is the