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Study of the magnetization behavior of ferromagnetic nanowire array: Existence of growth defects revealed by micromagnetic simulations

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ABSTRACT

High aspect ratio nanowires were electrodeposited in nanoporous anodic alumina template by a potentiostatic method. The angular dependence of the coercive field and remanence magnetization extracted from magnetometry measurements are compared with micromagnetic simulations. Inclusion of magnetostatic interactions between Ni nanowires in simulations is required to explain some of the properties of the magnetization reversal. However, it is not sufficient to reproduce fully the angular dependence of the coercive field. Due to the polycrystalline nature of nanowires and thus to the presence of grain boundaries, defects are included in simulations. A good agreement between theory and experiment is then clearly highlighted, in particular in the nanowire easy axis direction. The achieved results allow a description of several experimental data published in the literature and consequently to get a better understanding of reversal mechanisms that operate in such nanowire arrays. A complementary study of composite nanowire array is successfully performed to prove the adequacy of the simulations method to describe the magnetic properties of nanowire array.

1. Introduction

During the last decades, magnetic investigations of ferromagnetic nanowire arrays were extensively performed due to their specific properties with respect to bulk materials or thin films [1,2] and several potential applications in microwave filters [3], nanosensors [4] or high density magnetic data storage devices proposed [5–9]. For such applications, engineering magnetic arrays samples with desired coercivity and remanence is highly desirable. These properties are directly related to the processes of magnetization reversal which occur in such material. Their studies are consequently crucial. For a magnetic cylinder assumed to be a single domain particle, it is well recognized that the magnetization reversal can be modeled by coherent rotation [10] and curling [11] modes. Their relative intensity depends on the exchange and demagnetization energies and thus on the geometrical parameters: nanowire radius and aspect ratio (length-to-width ratio) of the nanowire [12,13]. Radius values much lower than a critical radius promote the coherent model reversal while larger value leads to the appearance of the curling reversal process [2]. In nanowire array, the magnetostatic interactions among the nanowires have a strong influence on their magnetic properties [14–16]. Numerous studies were devoted to the investigation of the reversal mechanisms and more especially to angular dependence of coercivity and remanence [17–19]. However, describing these angular dependencies in terms of micromagnetic modeling remains a challenging task [20].

Experimentally, the development of the template method using electrodeposition techniques is an ideal tool for the elaboration of nanowire arrays [21]. Indeed, the porous alumina membranes are known to provide ideal well defined periodicity of pores with well controlled structural parameters such as diameter, inter-pore distance and membrane thickness [22,23]. If a perfect filling of the template pores occurs [24], the nanowires should retain the size, the shape and the arrangement of the pores. In this case, micromagnetic calculations [25] are particularly suitable to study the magnetic properties of such nanowire arrays with a perfect symmetry and an ideal cylindrical geometry. The quality of the simulations is then related to the number of interactive wires which can be included in calculations [15,26]. Unfortunately, electrodeposition method does not guarantee a complete and homogeneous filling of the pores [27] and polycrystalline wires with a large number of grains could be present [28]. The influence of such grains on the reversal mechanism of ferromagnetic nanowire arrays is not well established especially on the angular distribution of both the coercivity and remanence. Micromagnetic simulations which take into account such effects are consequently of first interest and should serve as guidelines to explain the numerous

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experimental results which exist in literature. The aim of the present work concerns the investigation of the presence of defects in ferromagnetic nanowire and their influence in the angular distribution of the coercive field and remanence. For that purpose, ferromagnetic nickel nanowires arrays were elaborated due to the extensive works related to such nano-objects [29–34].

2. Experimental procedure

Nickel nanowires were synthesized in pores of Anode Aluminum Oxide (AAO) templates using constant potential of -1.1 V with respect to an Ag/AgCl reference electrode at room temperature. AAO templates are used because they have nearly uniform pores that are parallel and perpendicular to the membrane plane [35]. Elaborated nanowires show a nearly uniform diameter along the length contrarily to polycarbonate template [36]. A graphite hollow cylinder of large surface area was used as a counter electrode. The AAOs used in our experiment were purchased from Synkera Technologies, Inc. with nominal pore diameters of $d = 18 \pm 3$ nm, thickness of about 50 ± 1 μm and averaged porosity p of $10\% \pm 3\%$. This type of membrane features uniform cylindrical pores penetrating the entire thickness of the membrane. This porosity means that the distance a between the successive wire centers is close to 54 nm. By employing radiofrequency sputtering technique, a continuous layer of Au (50 nm thick) was deposited onto one side of the AAO membrane to serve as working electrode. The aqueous electrolyte was prepared from 262.84 g l^{-1} $NiSO_4$, $6H_2O$ and 20.40 g l^{-1} H_3BO_3 [37], using analytical-grade salts and deionized water (MilliQ, Millipore). The length of the synthetized nanowires is close to 4 μm.

Morphological and structural characterizations were performed using transmission electron microscope (TEM) JEOL JEM 1400 and X-ray diffraction. Magnetic measurements were performed at room temperature using a vectorial vibrating sample magnetometer (VSM) at room temperature 300 K [38].

3. Micromagnetic modeling

Micromagnetic calculations based on the finite-element method were performed using the NMAG modeling package [39] in order to compute the static magnetization configurations of the Ni nanowire array and to analyze the angular dependence of the coercivity. These configurations correspond to magnetization states obtained when the magnetization has converged to a stable configuration for a given applied field. The program solves the Landau–Lifshtiz–Gilbert (LLG) equation. The Gilbert damping constant a value was set to 0.5 according to value commonly used for static calculation [15,39]. The nanowires were meshed into tetrahedral elements of irregular size and shape with the program Netgen [40]. In each element, the magnetization was calculated at the nodes (corner points) of the tetrahedron. The mesh was chosen to insure that the distance between two corner points (nodes) of the tetrahedron is smaller than the exchange length $l_{ex} = \sqrt{2A/(\mu_0 M_S^2)}$ where A is the exchange stiffness and M_s the saturation magnetization. The chosen exchange stiffness $A = 10.5$ pJ/m and saturation magnetization $M_s = 4.14 \times 10^5$ A/m, leading to an exchange length of 9.87 nm, are characteristic of ideally soft nickel particles [13]. The effective field that appears in the LLG equation includes the contributions of the Zeeman energy, the exchange energy, the stray field energy and the crystalline anisotropy energy. In our calculation the anisotropy magnetocrystalline weak compared to the shape anisotropy for Ni nanowires has been neglected [41].

Our micromagnetic simulations were carried out for different cases. Firstly, isolated nanowire calculations were made to understand the magnetic properties inherent in a single nanowire: anisotropy, magnetization reversal. Secondly, several interactive nanowires ordered in a hexagonal array (finite size array) were used in the calculation in order to bring out the role of magnetostatic interactions on the magnetic properties. This kind of calculation is sensitive to the number of nanowires used in the array and is subject to side effects related to the finite dimensions of the array. Finally, virtual copies of the finite size array were considered in calculation in order to approach the periodic boundary conditions of a real nanowire sample [15].

4. Results and discussion

4.1. Morphology and structure

TEM observations of the Ni nanowires were performed by dissolving the alumina membrane in an 1 M NaOH bath. The nanowires were rinsed with water and ethanol and then maintained in an ethanol solution. A drop of this solution was deposited on copper TEM grid. The morphology of one Ni nanowire is shown in Fig. 1a. The diameter of the nanowire is equal to the pore diameter of the membrane. However, the level of gray indicates that the

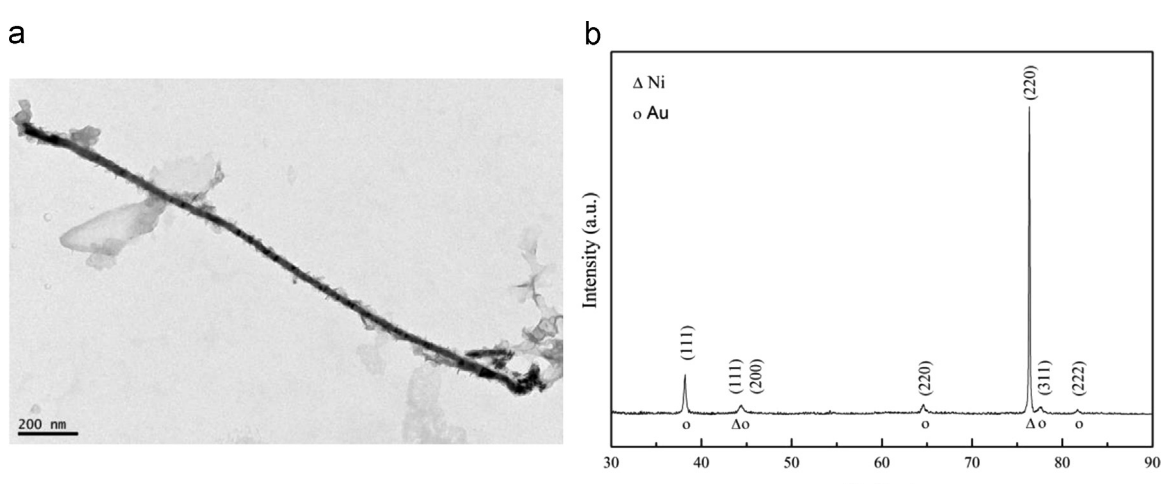

Fig. 1. (a) TEM image of a 18 nm diameter Ni nanowire after removal from the porous alumina template. (b) XRD pattern of the Ni nanowire arrays embedded in the AAO template.