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Magnetic behavior of $Ni_xFe_{(100-x)}$ ($65\leqslant x\leqslant 100$) nanowire arrays

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Abstract

Arrays of magnetic nanowires with composition $Ni_xFe_{(100-x)}$ ($65\leqslant x\leqslant 100$), 35 nm in diameter and 2000 nm long have been prepared by electrodeposition filling of highly ordered nanoporous alumina membranes. Long-range order of nanopores, with crystalline domain size of around 2 μm^2 and 105 nm lattice parameter of hexagonal symmetry, is achieved by self-ordering process, and characterized by SEM and AFM. Magnetic behavior of the arrays has been determined by VSM. Maximum coercivity of around 1.23 kOe and reduced remanence (about 0.8 saturation magnetization) is observed for $x=77$, while minimum values are observed for $x=100$. Detailed AFM and MFM studies allow us to gain additional information of the filling degree of pores which can result in a distributed nanowires length that finally correlates with a deterioration of macroscopic magnetic behavior of the array.

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Keywords: Nanowires; Nanoporous membrane; Coercivity; Magnetic force microscope

1. Introduction

During the past years, a huge effort is being made on the development of arrays of highly ordered nanostructures due to the potential applications in a wide range of areas as semiconductors, magneto-optics, biomedical applications, and various sensor devices or magnetic storing [1–3]. A number of methods are employed to fabricate nanoscale magnetic structures, for example, electron-beam, X-ray or imprint lithography [4,5]. Less sophisticated and cheaper techniques are also used involving templates with a given ordering thus allowing the preparation of arrays of magnetic nanowires [6,7]. Particularly, nanoporous alumina membranes are probably one of the best examples of such templates where magnetic nanowires can be prepared by filling the pores by an electroplating technique [8]. Arrays with high-order hexagonal symmetry can be then produced whose diameter can be controlled between 20 and 200 nm and the lattice parameter in the range from 65 to 500 nm. Previous studies have mainly focused on pure magnetic elements as Fe, Ni and Co [9,10].

In recent works, the influence of the ordering degree of the arrays [11,12], and of the ratio nanowire diameter to interpore distance [13] has been reported. The

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objective of the present work has been to study the magnetic behavior of a series of highly ordered NiFe magnetic nanowire arrays with different compositions, and check the influence of geometrical and pore filling degree irregularities.

2. Experimental techniques

Highly ordered $Ni_xFe_{(100-x)}$ alloy nanowire arrays have been produced by electroplating and filling the nanopores of alumina membranes. Nanoporous membranes with long-range hexagonal ordering have been prepared by a two-step anodization process [14,15]. Nanopores self-order during the first anodization process of high-purity (99.999%) aluminum foil (Goodfellow). Parameters of the first anodization step determine the characteristics of the array as pore diameter, interpore distance and ordering degree of pores, while second anodization determines the length of the nanopores. NiFe nanowires are finally electrodeposited inside the nanopores using a 300 g/l of $NiSO_4 \cdot 6H_2O$, 45 g/l $NiCl_2 \cdot 6H_2O$ and 45 g/l H_3BO_3 plus different amounts of $FeSO_4 \cdot 6H_2O$ as solution. Alloy composition of $Ni_xFe_{(100-x)}$ nanowires ranges between $x = 65$ and 100. Diameter of nanowires is 35 nm, the interpore distance or hexagonal lattice parameter is 105 nm, and the length of nanowires is 2000 nm.

The structure of the nanoporous membranes has been determined by scanning electron microscope, SEM, and atomic force microscopy, AFM, while the chemical compositions have been analyzed with X-ray fluorescence analysis, XRF. Magnetic measurements of the arrays as a whole were performed in a vibrating sample magnetometer, VSM, whereas the magnetic state of individual nanowires was determined by magnetic force microscopy, MFM.

3. Experimental results and discussion

The quality of the geometrical characteristics of nanoporous alumina membranes, templates for the nanowire arrays, can be observed in Fig. 1.

Long-range ordering together with the existence of polycrystalline domains, reaching around 2 μm^2, is observed in Fig. 1a. Fig. 1b shows an SEM image of a membrane cross-section where the parallelism between nanochannels can be confirmed as well as its perpendicular orientation with regards to the membrane plane.

The effective magnetic anisotropy of the arrays can be deduced from the comparison between hysteresis loops with applied field parallel and perpendicular to the wire axis. Fig. 2 shows the hysteresis loops for a particular array of nanowires with composition $Ni_{73}Fe_{27}$ (similar results are obtained for the rest of the compositions). As observed, perpendicular loop is nearly non-hysteretic while the parallel loop exhibits large remanence to magnetic saturation ratio indicating the existence of an

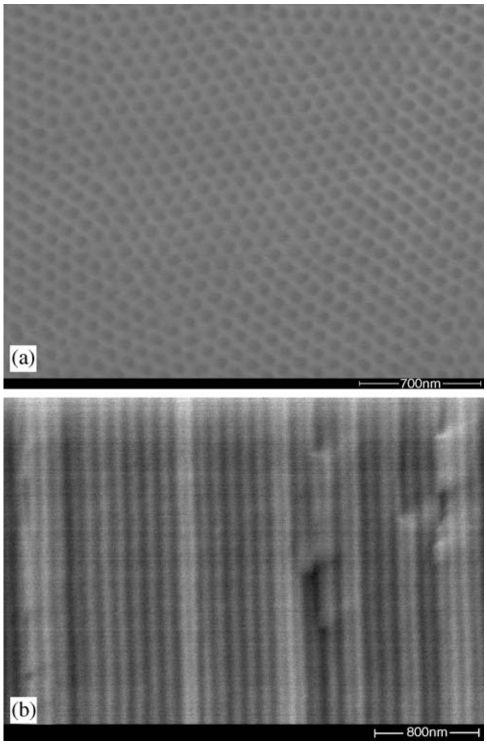

Fig. 1. SEM images of the (a) surface and (b) cross-section of a nanoporous alumina membrane.

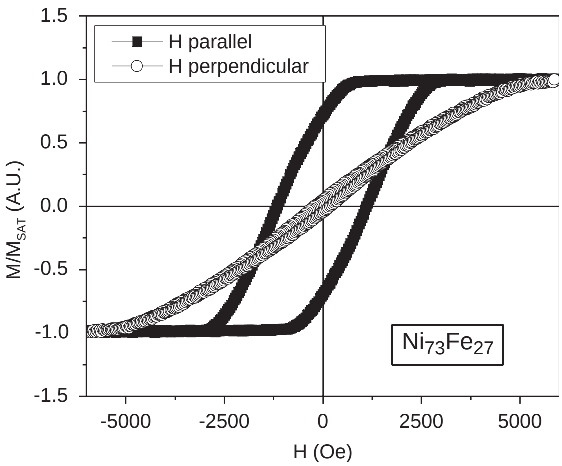

Fig. 2. Hysteresis loops of a $Ni_{73}Fe_{27}$ filled alumina membrane measured with applied field parallel (■) and perpendicular (○) to the nanowires axis.

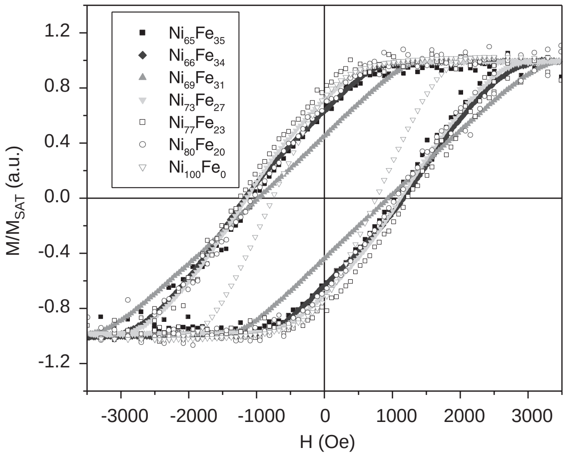

Fig. 3. Axial hysteresis loops of NiFe nanowires arrays with different compositions.

effective magnetic anisotropy with easy axis parallel to the nanowires.

Fig. 3 shows the compositional dependence of hysteresis loops corresponding to the magnetization process parallel to the nanowire axis. For a straightforward comparison, saturation magnetization for all the samples has been normalized.

As observed, although there is no dramatic compositional dependence, the optimized behavior with the larger remanence to saturation ratio, $M_r/M_s = 0.79$, and coercivity, $H_c = 1232\,\text{Oe}$, is observed for the nanowire composition with $x = 77$. It is to be particularly noticed that the increase of coercivity of the NiFe nanowire arrays in comparison with the Ni nanowires array exhibit a reduced coercivity of $H_c = 780\,\text{Oe}$.

The reduced values of coercivity and particularly the remanence observed for the $Ni_{69}Fe_{31}$ array should be also mentioned. Geometrical characteristics of this array have been analyzed in more detail in order to determine its anomalous magnetic behavior. The AFM images in Fig. 4 reveal the existence of filled and empty pores in the $Ni_{69}Fe_{31}$ array. From the analysis of the AFM profiles performed in different images corresponding to a variety of nanowires composition, we can conclude that the length of the nanowires is similar in all the samples except in the case of $x = 69$ where a length distribution is observed. This irregular nanoporous filling distribution is thus confirmed to significantly affect the magnetic behavior of an array.

The MFM image in Fig. 5 corresponding to the same array shows black and dark contrast corresponding to the wires with the magnetic moment oriented up and down. In addition, intermediate contrast is found at the positions of empty pores.

In conclusion, it is firstly shown that there is no significant compositional dependence of magnetic

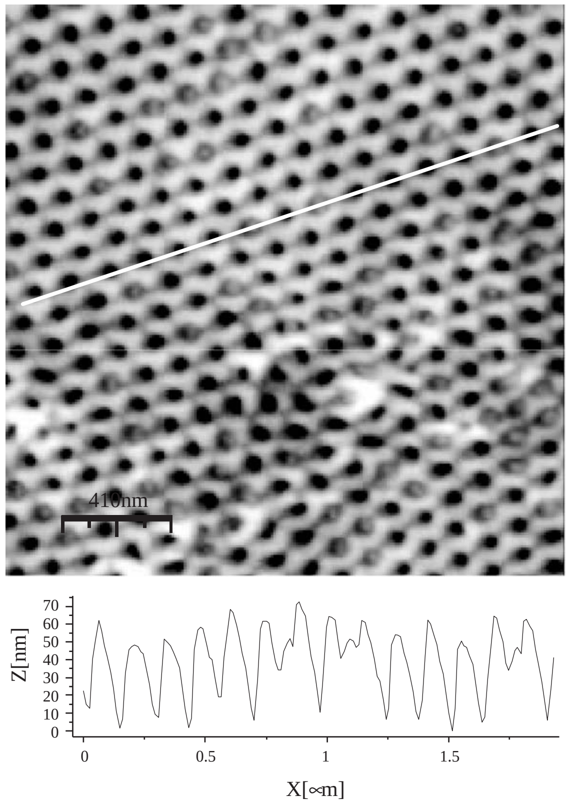

Fig. 4. The AFM image of $Ni_{69}Fe_{31}$ array of nanowires, and filling profile along an indicated orientation.

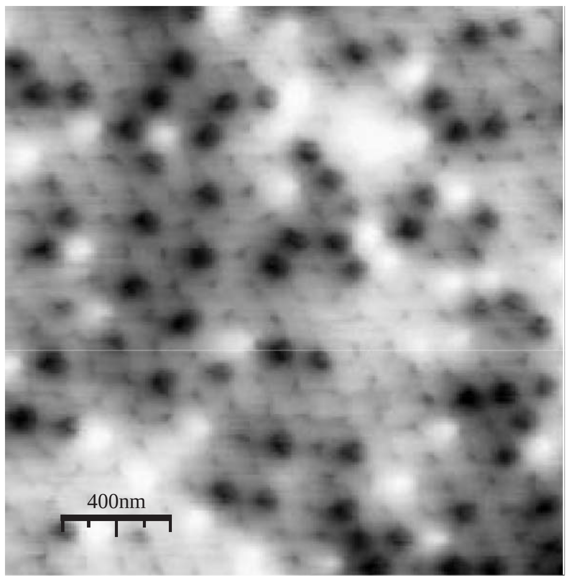

Fig. 5. An MFM image of $Ni_{69}Fe_{31}$ array of nanowires.

characteristics of $Ni_xFe_{(100-x)}$ ($65 \leqslant x < 100$) nanowire arrays except for an optimization with regards to pure Ni arrays. However, a significant deteriorated magnetic behavior has been found for the $Ni_{69}Fe_{31}$ nanowire array. The observed variety of nanowire lengths is correlated to the reduced permeability, coercivity and remanence observed for that array which are tentatively ascribed to an increased magnetostatic coupling among the nanowires.

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