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Coercive field behavior of permalloy antidot arrays based on self-assembled template fabrication

K.R. Pirota[a,*], P. Prieto[c], A.M.J. Neto[b,d], J.M. Sanz[c], M. Knobel[b], M. Vazquez[a]

[a]*Instituto de Ciencia de Materiales de Madrid—CSIC, Campus Cantoblanco, 28049 Madrid. Spain*
[b]*Instituto de Física "Gleb Wataghin", Universidade Estadual de Campinas—UNICAMP. C.P. 6165 Campinas, SP, Brazil*
[cc]*Departamento de Física Aplicada, Universidad Autónoma de Madrid. Campus de Cantoblanco, 28049 Madrid. Spain*
[d]*Departamento de Física, Universidad Federal do Pará, Campus universitário do Gama, 66075,110 Belém_PA. Brasil*

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Abstract

High-density magnetic antidot arrays have been fabricated by deposition of $Fe_{20}Ni_{80}$ thin films on self-assembled nanoporous alumina membranes (NAM) with high-order hexagonal symmetry. The magnetic properties induced by the size and the geometry configuration of the holes introduced in a $Fe_{20}Ni_{80}$ thin film are discussed based on hysteresis loops measured as a function of temperature. The precursor NAMs have pore diameters ranging between 35 and 95 nm (55 and 75 nm after the film deposition) and a lattice parameter of 105 nm. An enormous increase of coercitivity, as compared with the corresponding continuous films, was observed for temperatures between 2 and 300 K. This effect depends on the size and surface density of holes in the $Fe_{20}Ni_{80}$ antidot arrays. Rutherford backscattering spectrometry (RBS) measurements were performed in order to better clarify the magnetic material that was eventually deposited within the NAM pores.

Keywords: Magnetic antidots; Coercive field; Nanostructured materials; Alumina membrane

1. Introduction

Recently, theoretical and experimental studies have demonstrated that the magnetic properties of thin films can be controlled by the artificial introduction of small holes on them [1–4]. This procedure results in a magnetic thin film with periodic nonmagnetic inclusions, which is usually referred to as magnetic antidot array. These nanostructures are promising candidates for a new generation of ultra-high-density magnetic storage media, mainly due to the absence of the superparamagnetic limit, once there is no isolated small magnetic entity. The holes introduce shape anisotropies that allow the nucleation and movement of domain walls. In those systems, properties such as magnetoresistance, coercivity, permeability and magnetization reversal can be controlled [1–5]. Most of the works performed on magnetic antidot arrays are on submicron or micron scales and are obtained by the use of e-beam lithography [1–3]. An alternative technique that is being increasingly employed to produce antidot arrays with characteristic sizes around 100 nm makes use of nanoporous alumina membranes (NAM) as a precursor template. In this way, the nanostructure antidot array is obtained by growing magnetic thin films onto the NAM surface, which result in a magnetic antidot nanostructure with hole sizes as small as 20 nm [4,5].

In this work we report the use of NAM to fabricate magnetic antidot arrays, and we discuss the magnetic effect induced by the size and the geometry configuration of the holes introduced in a $Fe_{20}Ni_{80}$ thin film. We have mainly focused the work on the strong effect produced by the antidots in the coercive fields. We have demonstrated that by controlling the size and the density of holes, the coercive field can be systematically tailored.

2. Experimental

The NAMs were fabricated using the so-called two-step anodization process [6] in oxalic acids. The obtained

*Corresponding author.
E-mail address: kleber.pirota@uam.es (K.R. Pirota).

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membranes show a porous diameter of 35 nm and have a distance between them of 105 nm, which can be modified by a heat treatment in phosphoric acid (5% in volume) at 35 °C. Such treatment increases the porous diameter in a rate of 2 nm/min of acid etching, keeping fixed the interporous distance [1].

The magnetic antidots were fabricated by deposition of $Fe_{20}Ni_{80}$ thin films by ion beam sputtering (using a $Fe_{20}Ni_{80}$ target) on the upper surface of the membranes, replicating the array of nanoholes of the substrate and resulting in films with an array of antidots. The energy and total current for the sputter ion gun were 500 eV and 10 mA, respectively, giving a deposition rate of ~0.3 Å/s controlled by a quartz crystal monitor. The base pressure before deposition was 2×10^{-7} Torr. For comparison we have also grown in the same deposition process continuous $Fe_{20}Ni_{80}$ thin films on Si substrates. During the deposition process, the substrate temperature was kept at 200 °C. The samples were capped with a 3 nm Cu layer to prevent the oxidation of the magnetic thin film and the antidot arrays for "ex situ" characterization. The morphology of the antidot arrays was determined by scanning electron mycroscopy (SEM) and Rutherford backscattering spectrometry (RBS). In the case of RBS experiments, 3.7 MeV $^4He^+$ ions have been used at 7° from normal incidence to obtain the backscattering depth profiles of the different samples with solid-state detectors in the horizontal plane at 170.5° and 165°. The magnetic properties of the samples were studied in a temperature range between 2 and 300 K using both vibrating sample magnetometers (VSM) and SQUID magnetometers. Magnetization loops were measured with the applied field parallel and perpendicular to the antidot arrays plane. In addition, the angular dependence of the hysteresis loops was measured by an in-plane angular rotation from 0° to 360°, every 10° with a precision of 0.5° in order to determine the magnetic in-plane anisotropy distribution.

3. Result and discussion

Fig. 1 shows the SEM images of the precursor NAM template with 95 nm pore diameter and 105 nm lattice parameter (a) and after 80-nm-thick deposition of $Fe_{80}Ni_{20}$ onto its surface (b). The deposition reduced the antidot pore diameter to about 75 nm. Those images reveal a high hexagonal order degree in the antidot configuration that retains the same shape as the templates. The SEM images also indicate the high uniformity of the pore diameter size. The magnetization curves (not shown), with applied field parallel and perpendicular to the sample plane, for the magnetic continuous thin film and studied antidot arrays clearly show a magnetic anisotropy with an easy plane magnetization. The in-plane remanence and loop squareness are larger for the continuous film and decrease for the antidot arrays. These results agree with previous results obtained by Vovk et al. [5] that states there is a noncollinear spin configuration around the pores that promote incoherent magnetization reversal, which result in reduced remanence.

In order to better investigate the in-plane anisotropy, hysteresis loops have been measured by rotating the sample with respect to the direction of the in-plane applied magnetic field. In Fig. 2, one can see the dependence of the coercive field (H_c) as a function of the direction of external in-plane applied magnetic field for the continuous film deposited onto a Si substrate and for the antidot arrays with 25, 55 and 75 nm pore diameter (fixed 105 nm of lattice parameter), respectively. The behavior of the coercive field (obtained from in-plane and out-of-plane hysteresis loops, not shown) indicates that, even for the largest antidot size, the characteristic in-plane anisotropy of the magnetic thin film (that originates from the deposition method) remains in the antidot configurations. Vavassori et al. [3] have found that on permalloy antidot arrays with characteristic sizes on the micrometer range, the anisotropy of the arrays is clearly related to the antidot lattice symmetry. In our case, as is well known, the hexagonal order degree depends on the first anodization time [6]. For longer first anodization process the pores in the NAM are better ordered. All the samples studied in this work are produced with 24 h of first anodization and present similar degrees of order. Further experiments with increasing and decreasing this time are still being performed. As one can see in the figure, the continuous

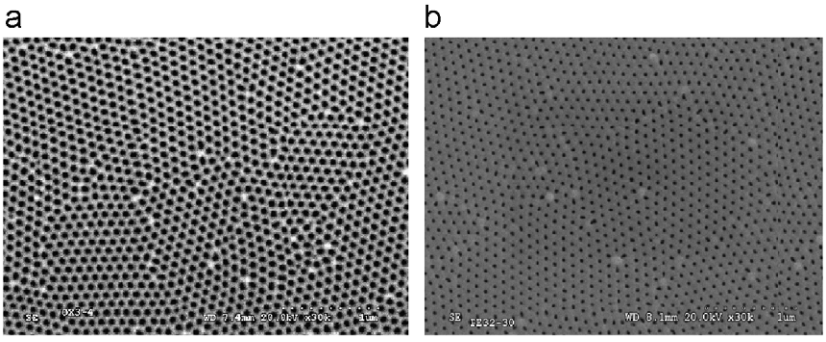

Fig. 1. SEM images of the NAM template with 95 nm pore diameter and 105 nm lattice parameter (a) and after 80-nm-thick deposition of $Fe_{80}Ni_{20}$ onto its surface (b).