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Ferromagnetic resonance investigation in permalloy magnetic antidot arrays on alumina nanoporous membranes

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ABSTRACT

The magnetic properties of $Ni_{80}Fe_{20}$ antidot arrays with hole diameters of 18 and 70 nm fabricated by a template-assisted method were investigated using the ferromagnetic resonance technique. Tuning the antidot arrays by changing the hole diameter enables control on the angular dependence of the ferromagnetic resonance field. The scanning electron microscope images reveal a quite regular hexagonal arrangement of the pores, however the angular dependence of the resonance field do not exhibit the six-fold symmetry expected for this symmetry. Micromagnetic simulations performed on a perfect hexagonal lattice, when compared with those made on our real system taken from the scanning microscope images, reveal that the presence of defects in the antidot lattice affects the ferromagnetic resonance field symmetry.

1. Introduction

Patterned nanomagnets are of great interest from both, fundamental and applied viewpoints. For a fundamental viewpoint, nanomagnets offer by virtue of their low dimensionality, a wide range of novel physical properties that are not encountered in their continuous bulk counterparts. In addition, magnetic nanoelement arrays have received a great deal of attention because of their potential applications in high-density magnetic recording media and in systems performing logic operations [1–6]. Among these structures, magnetic antidot arrays, which consist in a mesh of “holes” embedded in a continuous magnetic film, show novel magnetic configurations. The presence of the ordered non-magnetic holes induces a demagnetization field distribution, which can dramatically affect both, the static and dynamic properties of the magnetic system. From the static point of view it has been observed that the presence of holes affects the magnetization reversal, the coercive field and the intrinsic magnetic anisotropy of the film [7–13]. From the dynamical point of view it has been observed the presence of ferromagnetic resonance modes whose frequencies can be tuned by varying the holes dimensions, symmetry of the lattice and external magnetic field [14–19]. Among the experimental techniques used to investigate the magnetic properties of magnetic antidot arrays, ferromagnetic resonance (FMR) has been shown to be one of the most sensitive techniques in detecting effective fields associated with the magnetic anisotropies [20–24].

In this work, using the FMR technique we investigate the magnetic properties of $Ni_{80}Fe_{20}$ (Permalloy) nanometric antidot arrays with pore diameters of 18 nm and 70 nm fabricated using porous anodic aluminum oxide (AAO) membrane as template. We study the effect of the increase in the pore diameter on the angular dependence of the FMR field and show that the presence of defects in the lattice affects its symmetry. To analyze the experimental findings, micromagnetic simulations performed on a perfect lattice of antidot were compared with simulations made on a real image extracted from a scanning electron microscope (SEM) image [25]. The simulations qualitatively agree with the experimental results and indicate that in samples with defects, the micromagnetic simulations must be performed on images that recreate the pore distribution of the real systems.

2. Experimental details

The fabrication procedure of the antidot arrays includes (i) the preparation of the anodic alumina oxide (AAO) porous membranes with different pore diameters and (ii) the subsequent deposition of Permalloy (Py) on the AAO templates. First, 0.32 mm pure

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aluminum foils (99.999%) were electropolished for 5–10 min at a constant voltage of 10 V in a 75% C_2H_6O (Ethanol) and 25 W% $HClO_4$ (Perchloric Acid) solution at 5 °C. After this procedure, a two-step anodization process is used to fabricate the ordered antidot arrays. In the first step the samples are anodized at a constant voltage of 40 V in a 0.3 M $H_2C_2O_4$ (oxalic acid) solution and at a constant voltage of 25 V in a 0.3 M H_2SO_4 (sulfuric acid) solution, both at 20 °C for 8 h. These anodized layers were etched at room temperature for 12 h in a solution of 7 g of H_3PO_4 (phosphoric acid), 1.8 g $H_2Cr_2O_4$ (chromic acid) and adding H_2O up to complete 100 ml. The second anodization step is carried out for 6 h in the same conditions as the first anodization step, obtained the AAO membranes with a pore size of 50 nm in diameter in the case of oxalic acid and 18 nm in the case of sulfuric acid. Subsequently, the pores were widened in 5% phosphoric acid at 36 °C for 5–10 min to control de pore diameter of the AAO. The pore diameters obtained were close to 70 nm for the case of oxalic acid and close to 18 nm for the case of sulfuric acid. The obtained membranes present highly ordered pores of lattice constant of 100 nm for oxalic acid and 30 nm for the case of sulfuric acid.

The magnetic antidot arrays were obtained by deposition of Py films with 40 nm thicknesses onto the above-mentioned AAO porous templates by DC magnetron sputtering at room temperature. The base pressure in the chamber was below 1×10^{-6} Torr, and the Ar pressure during deposition was maintained at 3 mTorr. For comparison, the same magnetic structure was deposited on a glass substrate. Fig. 1 shows the SEM images of the Py antidot arrays with average hole size of 18 nm and 70 nm. The dark areas of the SEM images correspond to the pores, and the bright areas correspond to the magnetic layer supported by the pore walls. As observed, the images reveal a quite regular hexagonal arrangement of the pores.

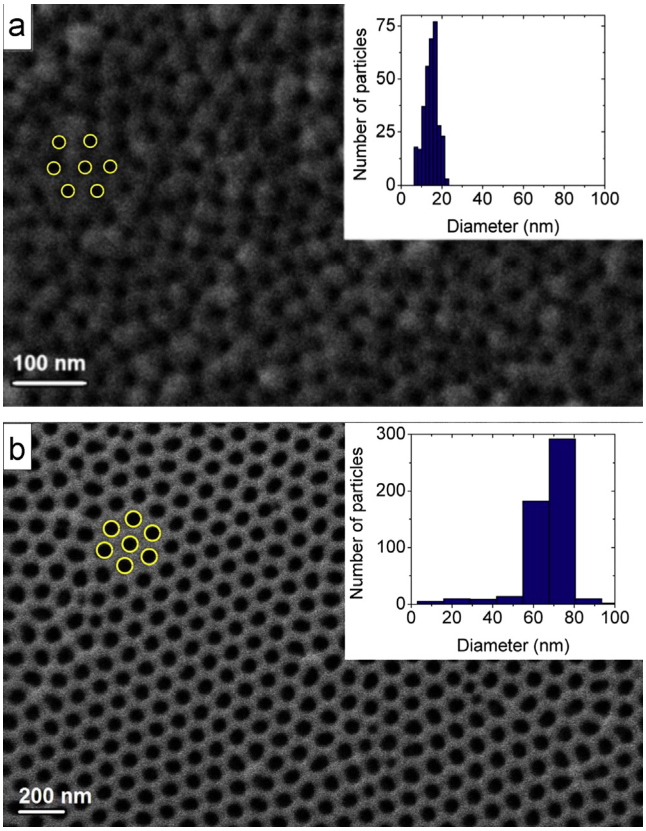

Fig. 1. Scanning electron microscope (SEM) images of the $Ni_{80}Fe_{20}$ antidot arrays with average pore diameter of (a) 18 nm and (b) 70 nm. For an eye guide, in both figures yellow circles denote the pore edges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The FMR measurements were carried out with a Bruker EMX-1572 spectrometer (9.8 GHz) at room temperature using a microwave cavity operating at 100 kHz magnetic field modulation frequency. The sample, placed at the center of the cavity, was mounted on the tip of an external goniometer that could be rotated to allow the angular measurement of the FMR field H_R determined by fitting the derivative of the absorption spectrum.

3. Micromagnetic simulation

In order to interpret the experimental results we performed micromagnetic simulations in a perfect hexagonal lattice with perfectly circular holes, and compared these with the simulations made on a SEM image that, previously treated [25], can be read by the 3D OOMMF package [26]. It is noteworthy that simulated samples do not correspond to the real sample. This is because the real sample has a size close to 2×2 mm^2, including about 2×10^8 holes, and the simulated systems considered simply a size of 1×1 μm^2 without periodic boundary conditions, both including about 120 holes. Thus, numerical simulations are intended to give a qualitative explanation of the effect of disorder on the magnetic properties of the antidots, and do not try in any way to reproduce the experimental results. For the simulations the systems were divided in a mesh of cubic cells of 2 nm^3 with uniform magnetization. The parameters used for Permalloy were: saturation magnetization $M_S = 860\times10^3$ A/m and exchange constant $A = 12\times10^{-12}$ J/m. Note that the cell sizes are smaller than the exchange length [27].

4. Results and discussion

Fig. 2 shows the in-plane FMR spectra of the Py thin film (Fig. 2(a)) and its corresponding antidot arrays of 18 nm (Fig. 2(b)) and 70 nm (Fig. 2(c)) of holes diameter. As observed, in comparison with the continuous magnetic film where the FMR spectrum has a single resonance mode at a resonant magnetic field $H_R = 1800$ Oe, there are two resonance modes clearly identified in the spectra of the antidot arrays. For the antidot arrays with mean diameter of 18 nm (Fig. 2(b))

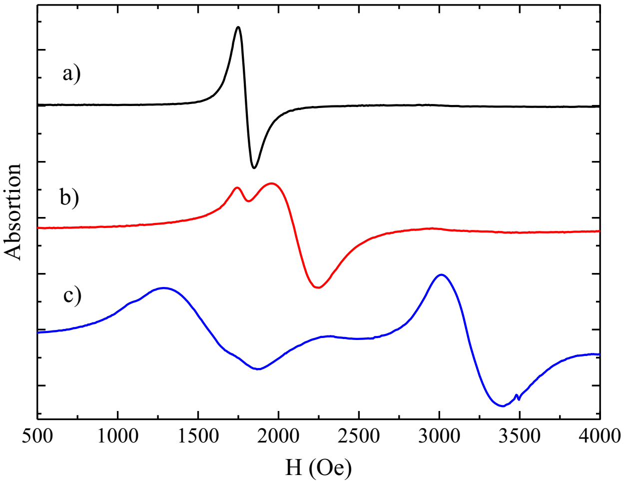

Fig. 2. The FMR spectra with applied in-plane magnetic field at $\varphi = 0^{\circ}$ for (a) the original continuous magnetic film and (b), (c) the antidot arrays with holes diameter of 18 nm and 70 nm, respectively.