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Preparation, structural characterization, and dynamic properties investigation of permalloy antidot arrays

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Regular nanosized structures are considered to be promising materials for magnetic information storage media with high density of information. Recently attention was paid to static and dynamic magnetic properties arising from dimensional confinement in such nanostructures. Here we present an investigation of permalloy antidot arrays of different thicknesses. Thin permalloy films of thickness ranging from 10 to 500 nm were deposited on nanoporous Al_2O_3 membranes with a pore size of 100 nm. It was found that additional ferromagnetic resonance peaks appear for film thicknesses below 100 nm, while films with larger thicknesses show resonance properties similar to continuous films. A comparison between the films deposited onto Si wafers and porous media was done. An evolution of the domain structures observed in MFM experiments was confirmed by micromagnetic calculations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853691]

Well-ordered arrays of nano-size objects attract a lot of attention due to their potential applications for ultrahigh density magnetic information storage. Among them are so-called antidot structures, which are arrays of pores instead of dots. Antidots are believed to have an advantage over nanodots as they are easier to prepare. Also, there is no superparamagnetic limit of information bit size, as there is for dot structures. Recently, numerous publications reported on the static and dynamic magnetic properties of antidot structures. In most cases, these antidots are submicron or micron size. For example, magnetic anisotropy and domain structure were analyzed for an antidot array of 1.6 μm size.[1] Dynamic properties of rectangular antidot structures with a pore size of 1.5 μm and interpore distance of 3–5 μm were reported.[2] Magnetic reversal for asymmetric antidots of 6–10 μm size was presented in Ref. 3. In contrast, there are only a few investigations that study structures with characteristic sizes around 100 nm. It was shown in Ref. 4 that it is possible to prepare an antidot structure with a pore size as small as 20 nm by deposition of Ni film on anodic aluminum oxide (AAO). The magnetic reversal and magnetotransport properties were analyzed and it was suggested that such technology is suitable to prepare materials that can be used for ultrahigh density storage media. However, in the quoted work no results on magnetic domain structure and dynamic properties were reported. In this work we report on the preparation of permalloy antidot structure on AAO substrates and an investigation of its magnetic structure, as well as static and dynamic magnetic properties.

Nanoporous AAO substrates were prepared using oxidation of high purity (99.999%) aluminum sheets. The details of the preparation procedure were reported elsewhere.[5] The thicknesses of the membrane and pore sizes were controlled by the current density and the anodizing time. AAO membranes with regular hexagonal arrangement of pores of 100 nm in diameter, about 100 nm spacing, and 280 nm thickness, were fabricated. Field emission scanning electron microscopy cross-sectional images[5] of the AAO membrane revealed uniformity of the pore diameter and high ordering of the array.

Permalloy films were deposited on the AAO membranes using a magnetron sputtering system with research S-guns. The base pressure before deposition was 1.1×10^{-7} Torr, and the argon pressure during deposition was 3.0 mTorr. The deposition rate was controlled by an INFICON IC 6000 quartz monitor and was kept at 0.1 nm/s. The films with thicknesses (d) in the range from 10 to 500 nm were prepared. Reference samples with the same thicknesses were deposited simultaneously on Si wafers. Magnetic properties of the films were studied using a Quantum Design MPMS 5S SQUID magnetometer at 300 K. The ferromagnetic resonance (FMR) was measured at 300 K using an X-band Bruker EMX300 EPR spectrometer with magnetic field in the film plane. The surface and domain structures of the deposited films were studied using a Digital Instruments Nanoscope IIIa scanning probe microscope.

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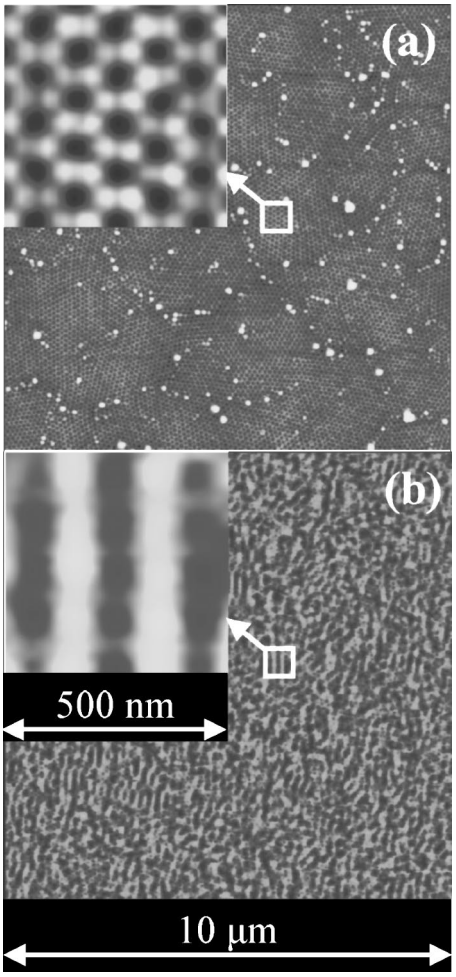

FIG. 1. Atomic Force Microscope (a) and Magnetic Force Microscope (b) images of 100 nm thick Permalloy film deposited on an AAO membrane.

It was found that increasing d up to 100 nm did not affect the size and the shape of the pores. The atomic force microscopy and magnetic force microscopy images of 100 nm thick film are represented in Fig. 1. It is clearly seen that the antidot structure retains the structure of the AAO membrane. Further increase of d leads to a rapid decrease in the pore size, and the film becomes continuous for thickness $d>200$ nm. The effect of film thickness (for $d<100$ nm) on the pore size is different from what was reported earlier[4] for Ni antidotes. Most probably, this discrepancy is caused by the structure of the AAO membranes and the difference in the deposition rates, which was lower in our case. Magnetic Force Microscope images also show that the barlike domains are pinned along the lines of pores (see the insets in Fig. 1). Micromagnetic calculations performed using JaMM code[6] confirm the pinning of the domain walls along the rows of the holes (Fig. 2). Formation of such domain structure is a clear indication that the density of magnetic recording $\sim 10\ \mathrm{Gbits/cm^2}$ can be achieved using 100 nm antidote arrays.

Magnetic hysteresis loops for the films of different thickness deposited on AAO and Si are presented in Fig. 3. For $d=10$ nm the loops are narrow and have a square shape for the films on both the AAO and on Si. However, the remanence is lower in the case of the AAO substrate. For d

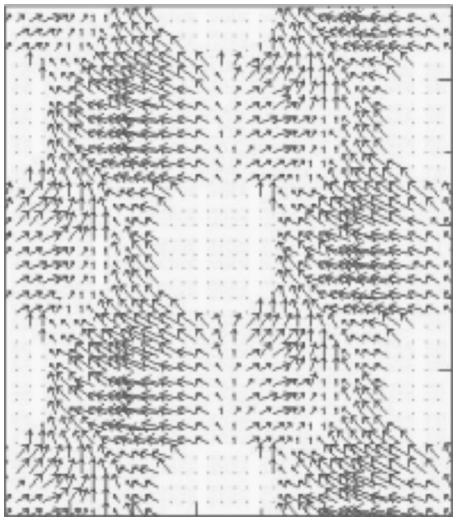

FIG. 2. Micromagnetic simulation of antidote spin structure using the JaMM code.

$=500$ nm hysteresis loops for the films on the AAO and Si substrates practically coincide. This is in good agreement with structural studies and confirms that for this thickness the film is continuous. Thus the pores are covered and the structure of the substrate does not affect the magnetization reversal. For the intermediate range of thicknesses, a gradual evolution of the hysteresis loops shape was observed. The loops for the films deposited on Si show higher remanence and squareness. The difference in magnetization reversal is

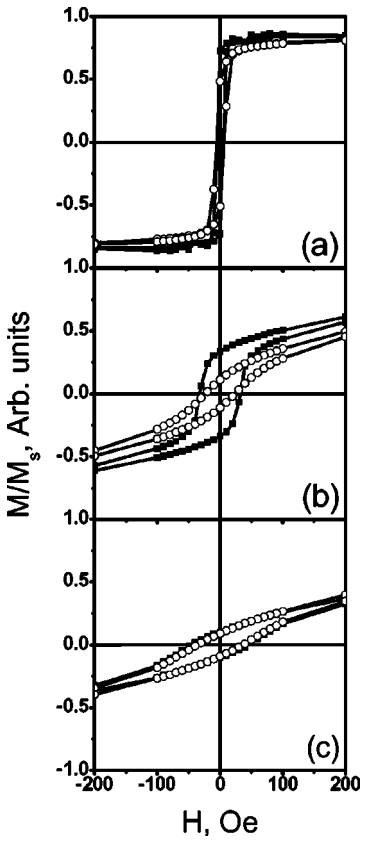

FIG. 3. Magnetic hysteresis loop of permalloy films of thickness 10 nm (a), 100 nm (b), and 500 nm (c) deposited on Si wafers (solid square) and AAO membrane (open circle).

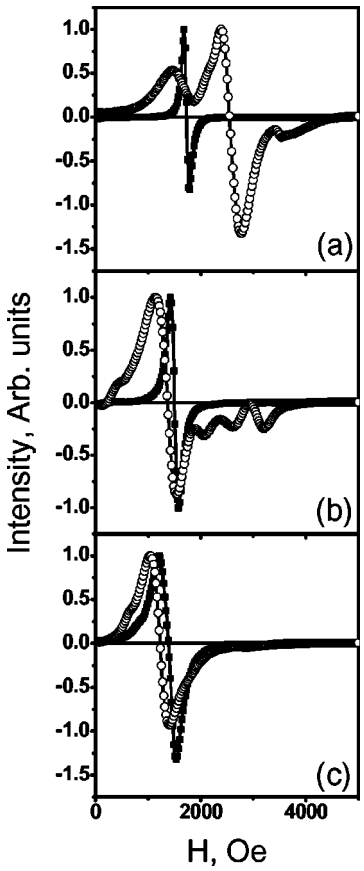

FIG. 4. FMR spectra of permalloy films of thicknesses 10 nm (a), 100 nm (b), and 500 nm (c) deposited on Si wafers (solid square) and on AAO membranes (open circle). Magnetic field was applied in the film planes.

caused by the differences in the topology of the films deposited on AAO. Computer simulations of the magnetization process show that the reversal begins in the vicinity of the pores where vortex states are formed. This noncollinear spin configuration around the pores promotes incoherent magnetization reversal, which results in reduced remanence.

FMR measurements provide additional information about magnetic properties of the films. FMR spectra recorded in the films are summarized in Fig. 4. A single sharp resonance line was observed in all of the films deposited on Si wafers. In contrast, the FMR spectra of the films deposited on AAO substrate consisted of multiple, broad resonance peaks. The appearance of additional modes is associated with the patterned structure of the films and reflects a lateral dimensional confinement. Previously, similar multipeak spectra were reported for magnetic dot arrays.[7,8] However, this is just a rough analogy, due to the different character of interaction inside dot and antidot arrays. Unfortunately, so far, there is no well-defined theory describing FMR for antidot structure. For small d, the main resonance peak is shifted toward high fields. This is connected with the decrease of the demagnetizing factor of the film due to the roughness of the surface. The increase of d leads to the shift of the resonance peak to a low fields area. For certain d the value of the resonance field becomes lower than that observed for the film deposited on Si substrate. This fact reflects the presence of an in-plane anisotropy in the antidot structure. However, to investigate the origin of such anisotropy, lithographically patterned antidot structures on flat surfaces are preferable. Finally at the highest d the spectrum became pretty close to the one observed in the film deposited on a Si wafer, which correlates with the magnetic data.

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