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Shape critical properties of patterned Permalloy thin films

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The effects of shape and edges in magnetic elements with reduced dimensions on the magnetization reversal of cross- and framed cross- shaped $Ni_{79}Fe_{21}$ (30 nm) films were studied. Remagnetization details in the strips of the patterned structures, which had 3 to 30 μm widths and ~100 μm lengths, were visualized by the magneto-optical indicator film technique. The magneto-optic images revealed three different types of the domain structure formation and evolution in the samples during their magnetization reversal: (i) spin rotation with growth and annihilation of a cross-tie structure in the strips perpendicular to the applied field, (ii) nucleation and fast motion of special boundaries, which consist of a number of coupled vortices located along both edges of the strips parallel to the applied field, and (iii) switching by ripple structure formation with macrodomain nucleation and domain wall motion in the large unpatterned part of the films. It was experimentally revealed that there exists a dependence of the critical field for nucleation and motion of domain walls in the parallel-to-field strips on their width and frame width. In particular, an inverse proportionality between this nucleation field and strip width was found in these strips having micrometer sized widths. Both experimental and simulation results show that, in cases (i) and (ii), the magnetostatic fields, which are formed on the edges of the strips and at their intersections, play a crucial role in the formation of spin inhomogeneities and switching of the samples.

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1. Introduction

Steady improvement of thin film growth and patterning techniques pushes the physical size of samples towards ever-smaller dimensions. Magnetic properties of the thin-film elements are by virtue of their small size very different from the same materials in bulk. In this case, the magnetization, *M*, distribution and reversal in thin films with restricted lateral sizes is mostly governed by the magnetostatic fields localized on their edges [1]. Manipulation of the size, shape, and orientation of the patterned thin films having a thickness of a Bloch wall width or less results in films possessing unusual properties [1–5]. Of fundamental interest is a precise knowledge of the 2D-dimensional surface magnetic structure and its evolution with field, *H*, application, and their dependence on the shape and size of these small magnetic elements.

In recent years, magnetic thin films patterned at the nanometer scale have become attractive for applications in magnetic random access memory (MRAM) with increased storage density [6,7], magnetic field sensors [8], spin transistors [7,9], and other devices. The most widely studied shape of thin-film elements has been rectangular and cross-shaped, due largely to the applicability of such structures to MRAM [6,7] and magnetic field sensors [8]. But there have also been studies of circular magnetic elements [10,11]. When the size of the magnetic structures becomes of the same order of magnitude as some characteristic magnetic length scale (domain wall thickness, magnetic exchange length, spin vortex width, and other stable or unstable magnetic perturbation sizes), or when the magnetic entities interact with each other, the dipolar interactions within the elements give rise to a configurational anisotropy and to a change in the coercivity. In this case, the size and geometrical configuration of the elements have caused modifications in their domain structure and play a significant role in controlling its evolution upon application of a magnetic field [1–4,10,12–17].

In particular, it was established there is a significant influence of shape and size on the hysteresis loops [3,16,17] and configurational anisotropy [3,4] in Permalloy (Py) thin nanostructures. In recent years, Kerr microscopy, magnetic force microscopy, and micromagnetic simulation studies have been conducted on the fabrication and characterization of planar magnetic microstructures fabricated as rectangles [1,2,4,12,13,16,17] and crosses [12,14,15] of sizes ranging from tens of nanometers to tens of micrometers. It was shown in these studies that the ground state (e.g., at $H=0$) of such thin-film elements may consist of one or a number of complicated domain structures including vortices and antivortices, "diamond" and Landau structures, and cross-tie

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structures. Such magnetic states are determined by the minimization of magnetostatic, exchange, and anisotropy energies which depends on the size, shape, orientation, thickness, and composition of the structures. In [17] a universal dependence of switching field of patterned magnetic nanolines as a function of the linewidth for Co and NiFe films of various thicknesses were reported. In particular, it was established that the coercive field in thin rectangular ferromagnetic films is proportional to the film thickness and inversely proportional to the width of strips, which ranged from 65 nm to 1130 nm.

However, despite the previous detailed experimental and theoretical investigations of the shape and size influence on the ground state of restricted thin magnetic films, the size and shape dependence of the kinetics of the domain structure transformation upon application of a field has not been studied sufficiently. Recently, new features of the magnetization reversal in both free and exchange-coupled (with an antiferromagnet IrMn layer on top) thin ferromagnetic (FM) $Ni_{79}Fe_{21}$ films [18–20] patterned in the form of a square mesh were revealed. Quite different micromechanisms and switching fields of the mesh strips were observed during magnetization reversal for *H* oriented parallel or perpendicular to the strips. Since it is well known, the ground state and reversal mechanisms are determined by the competition from different energy sources, the difference in reversal behavior depending on the orientation of *H* was primarily due to differences in magnetostatic energy which are known to be quite large [21] in such a system. Even this study, however, did not investigate the kinetics of the transformations. In this paper, we present both experimental and simulation results of the magnetization distribution and transformation kinetics during the reversal of microstructured Py thin films. The effect of shape and edges in the magnetic elements with reduced dimensions on the magnetization reversal of cross- and framed cross-shaped $Ni_{79}Fe_{21}$ films were studied in particular.

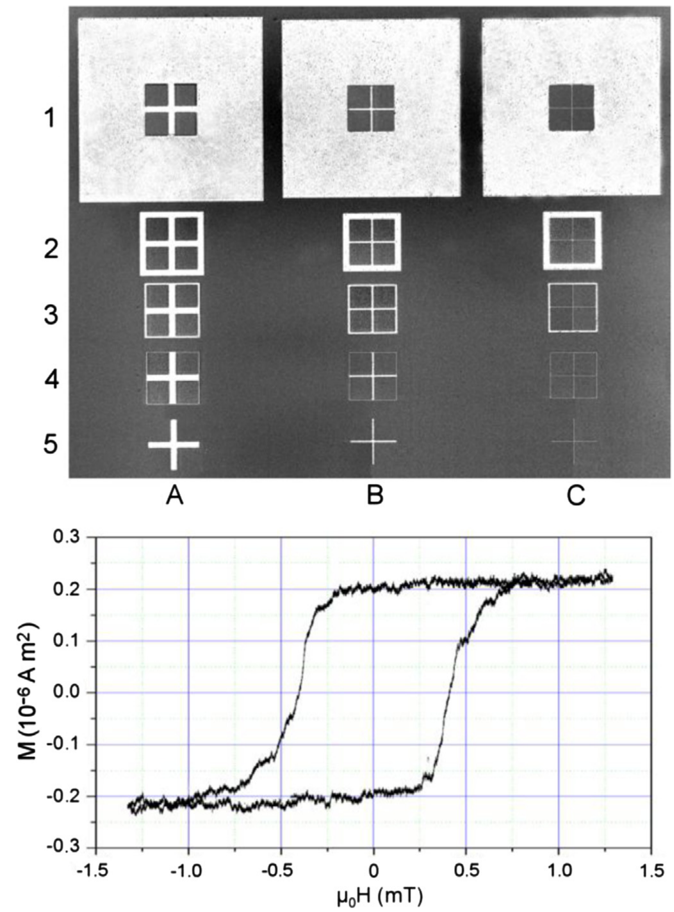

Fig. 1. Optical micrograph and macroscopic hysteresis loop of the patterned $Ni_{79}Fe_{21}$ structure.

2. Experimental procedures and simulation

We have used Permalloy (Py) $Ni_{79}Fe_{21}$, which is almost isotropic, so any anisotropy in the laterally restricted magnetic thin films must come from their shape. Thick polycrystalline $Ni_{79}Fe_{21}$ (30 nm) films were deposited by magnetron sputtering onto Si (100) wafers having a 250 nm thermal oxide on top. The films were then microstructured into crosses with and without frames (Fig. 1) by means of optical lithography. The strip width, *b*, was either 30 μm, 10 μm, or 3 μm (columns A, B, and C in Fig. 1, respectively) and the cross arms were ~100 μm in length. The widths, *d*, of frames were either 300 μm, 30 μm, 10 μm, 3 μm, or 0 μm (rows 1, 2, 3, 4, and 5 in Fig. 1, respectively). The field used during our magnetization reversal experiments was applied along the horizontal strips. The hysteresis loop of the whole FM film, patterned as shown in Fig. 1, was measured using a vibrating sample magnetometer. All magneto-optical (MO) measurements were performed at room temperature. Visualization of domain structures was provided during the remagnetization process using the magneto-optical indicator film (MOIF) technique [22,23]. Real time MO imaging was made using a charge coupled device (CCD) camera capturing 30 pictures per second while *H* was linearly varied. In this technique, a transparent Bi-doped yttrium iron garnet indicator film with an Al mirror bottom surface is placed on top of the sample to image the stray magnetic fields around the film edges and domain walls (DWs). In the absence of a magnetic field, the garnet magnetization is oriented in-plane, but it is deflected out of plane by perpendicular components of the stray field, $H_\perp$, around the sample. Using a polarized light microscope with slightly uncrossed polarizer and analyzer, MO images of the sample's magnetic structure are obtained in the reflected light due to the double Faraday effect of the indicator film. The black and white colors of the MO image correspond to opposite signs of $H_\perp$. In order to aid the reader, throughout all the MO figures of this paper, the *H* and *M* orientations are shown by white and black arrows respectively. The magnetization configurations were also calculated using the OOMMF software code [24]. Typical material constants for Permalloy were chosen: saturation magnetization value = 860 kA/m, exchange stiffness = 13 pJ/m, and magnetocrystalline anisotropy = 0 J/m^3. The discretization cell size was $30 \times 30 \times 30$ nm^3.

3. Results and discussion

Fig. 1 shows the hysteresis loop of the patterned film that was measured when the field was applied parallel to the horizontal strip in the $Ni_{79}Fe_{21}$ crosses. The sample has a small coercivity with practically zero magnetocrystalline anisotropy and magnetostriction. For this sample which possesses only shape anisotropy, Fig. 2 shows the reversal behavior of the whole FM patterned structure having a strip width of 30 μm. In this figure are MO images of various areas of the film, including the quasi-infinite unpatterned frame and the horizontal and vertical strips of the patterned part of the FM film, during its remagnetization from the positive saturated state (Fig. 2a) to negative saturation (Fig. 2f). Strong MO contrast of the magneto-optic signal caused by large stray fields is observed on the vertical edges of the frame and strips, whereas it practically vanishes at the horizontal edges. At the horizontal edges, the magnetic field, and consequently the