

Magnetic domain structure of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ nanoislands: Experiment and simulation

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We have studied the magnetic domain structure of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) nanoislands with dimensions on the order of 160~720 nm. Domain structures of (001)-oriented LSMO rectangular nanoislands exhibit single and multiple flux-closed domain states depending on aspect ratio. (110)-oriented rectangular nanoislands, with a strain-induced magnetically easy axis parallel to the long axis of the rectangle, exhibit single and two domain states depending on aspect ratio. (110) elongated hexagonal islands, with similar aspect ratios, uniformly exhibit single domain states due to the apparent suppression of domain nucleation at tapered edges. These results are consistent with object-oriented micromagnetic framework simulations of LSMO islands. © 2011 American Institute of Physics. [doi:10.1063/1.3544510]

I. INTRODUCTION

Understanding the nature of magnetism in geometrically confined ferromagnetic systems has been of significant interest from fundamental and technological perspectives. Many studies have focused on self-assembled or lithographically patterned ferromagnetic metallic compounds with possible incorporation into patterned media, magnonic crystals and magnetic logic circuits.¹⁻³ Recently, single domain permalloy $\text{Ni}_{0.8}\text{Fe}_{0.2}$ nanomagnets have been extensively studied for logic applications.³⁻⁵ In such a magnetically soft materials system, the shape anisotropy determines the magnetically easy axis. However, it has been recently predicted that the superposition of a biaxial anisotropy on the uniaxial shape anisotropy should stabilize the magnetic ground state of a single ferromagnetic nanoisland in a magnetic logic circuit.⁶ Therefore a good candidate material would be one that exhibits a biaxial magnetocrystalline anisotropy; this biaxial magnetocrystalline anisotropy combined with the uniaxial shape anisotropy will enable us to stabilize signal propagation in magnetic logic circuits.

A promising material for such magnetic logic applications is $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) that has been shown to exhibit high spin polarization and colossal magnetoresistance.⁷ Epitaxial LSMO thin films have been shown to exhibit in-plane biaxial anisotropy and uniaxial anisotropy^{8,9} depending on the choice of substrate and its orientation. Patterning of these complex oxide materials has been challenging. Optical lithography combined with ion milling has been used to pattern LSMO islands with limited success. This process has very low yield and gives rise to dome-shaped islands, i.e., whose thickness varies as a function of

the distance across the island.^{10,11} More recently, Takamura *et al.*¹¹ and Bettinger *et al.*¹² used e-beam lithography and ion implantation to pattern LSMO nanomagnets on the order of $500\text{ nm} \times 500\text{ nm}$ to $500\text{ nm} \times 1 \sim 2\text{ }\mu\text{m}$. The ion implantation suppresses the Curie temperature and saturation magnetization of the unprotected LSMO, thus leaving a paramagnetic region. This technique defines ferromagnetic islands in a paramagnetic matrix that offers the advantage of a planar profile. They found that domain structures of LSMO islands are determined by the competition among shape, magnetocrystalline and magnetoelastic anisotropy energies.¹⁰⁻¹²

In this paper, we have studied the magnetic domain structure of LSMO islands ranging in area from $160\text{ nm} \times 160\text{ nm}$ to $160\text{ nm} \times 720\text{ nm}$ in order to determine its viability as the basic building block of a magnetic logic circuit. Domain structures of (001)-oriented LSMO nanoislands evolve from flux closure to single domains while those of (110)-oriented nanoislands evolve from two domain to single domains with increasing aspect ratio. The differences can be attributed to the biaxial magnetocrystalline anisotropy in (001)-oriented LSMO versus uniaxial strain-induced anisotropy in (110)-oriented LSMO. In addition, tapering the edge of the islands promotes the formation of single domain states. These results are consistent with object-oriented micromagnetic framework (OOMMF) simulations of the LSMO nanoislands in a non-magnetic matrix.

II. EXPERIMENT

Epitaxial LSMO thin films, approximately 35 nm thick, were deposited on both (001)- and (110)-oriented SrTiO_3 (STO) substrates by pulsed laser deposition at 700 °C with a KrF excimer laser operating at 248 nm and fluence of $\sim 1\text{ J/cm}^2$. A bilayer of 20 nm polymethyl methacrylate and

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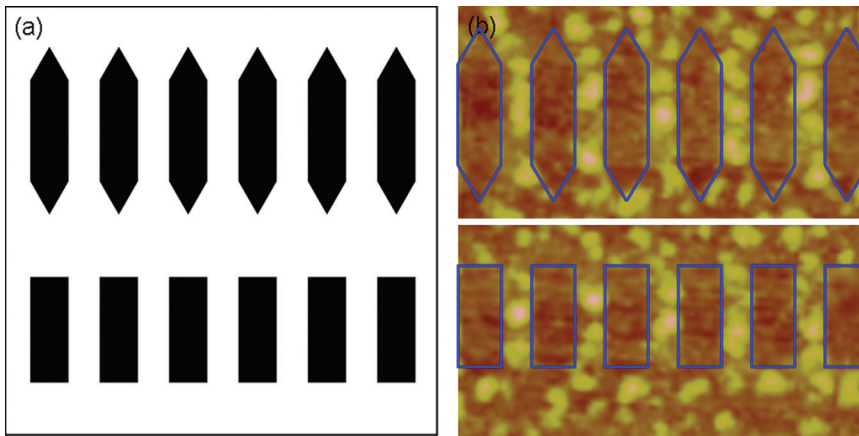


FIG. 1. (Color online) (a) The mask design showing hexagonal and rectangular nanoislands with size of $160 \text{ nm} \times 700 \text{ nm}$ and $160 \text{ nm} \times 440 \text{ nm}$, respectively, separated by 130 nm and (b) the corresponding atomic force microscopy image of the patterned islands.

200 nm hydrogen silsesquioxane was spin coated on LSMO. Nanoislands with rectangular and elongated hexagonal shapes as shown in Fig. 1(a) were patterned by e-beam lithography. The long axes of the nanoislands are oriented parallel to a magnetically easy direction. A subsequent Ar^+ ion implantation at 50 keV and a dose of $1 \times 10^{14} \text{ cm}^{-2}$ selectively suppresses the ferromagnetism in the areas not protected by resist. During the ion implantation process, the unprotected region experiences a volume expansion resulting in increased z -height by $2 \sim 5 \text{ nm}$. After the photoresist lift-off process, ferromagnetic islands embedded in a paramagnetic matrix are defined as shown in Fig. 1(b). In order to probe the magnetic domain structure, we used both photoemission electron microscopy (PEEM) and magnetic force microscopy (MFM). PEEM is an element specific, surface sensitive technique that provides us with the projection of the magnetic moment along the incident x -ray direction while MFM probes field gradients.

Figure 2 shows PEEM images of domain structures of LSMO nanoislands prepared on (001)-oriented and (110)-oriented STO substrates. It has been shown that in (001)-oriented LSMO films, magnetocrystalline anisotropy energy dominates and the films exhibit a four-fold symmetry with the easy axis along $\langle 110 \rangle$ directions.⁹ This four-fold symmetry manifests itself in what appears to be a four domain state in LSMO rectangular nanoislands prepared on (001) STO with dimensions of $160 \text{ nm} \times 440 \text{ nm}$ as shown in Fig. 2(a). We believe that this four domain state is in fact a manifestation of a multiple flux closure state due to the limited resolution of the PEEM microscope. As the aspect ratio decreases, (001)-oriented LSMO rectangular islands start to form two domain states which we believe to be a manifestation of a flux closure state again due to the limited resolution of PEEM. Our previous work on larger LSMO nanoislands on the order of 500 nm on a side clearly reveal the flux closure state.¹¹ In contrast to (001)-oriented rectangular islands, elongated hexagonal islands prepared on (001) STO show single domain states for all aspect ratios with the tapered edge appearing to suppress the formation of domains.

Domain structures of (110)-oriented rectangular islands evolve from oppositely magnetized two domain states to single domain states as the aspect ratio increases as shown in Fig. 2(b). Domain structures of elongated hexagonal islands

show only single domain states. For aspect ratios of $1:2.8$, (110) hexagons form single domain states due to the suppression of domain formation at tapered edges while (110) rectangles show two domain states. In (110)-oriented LSMO films, strain-induced magnetic anisotropy gives rise to a two-fold symmetry with the easy axis along [001] direction. By choosing the long axis of the island parallel to the strain-induced magnetically easy axis, we find that the strain and shape contributions add together to form a uniaxial anisotropy.^{9,11} Therefore, (110) islands do not form flux-closed domain states.

III. SIMULATION

We compared our experimental data with magnetic domain structures of LSMO nanoislands computed using OOMMF. The following parameters were used: a saturation magnetization of 400 emu/cm^3 (at room temperature), biaxial magnetocrystalline anisotropy constant of $1.6 \times 10^4 \text{ ergs/cm}^3$ for (001)-oriented LSMO and uniaxial strain anisotropy constant of $1.9 \times 10^5 \text{ ergs/cm}^3$ for (110)-oriented LSMO.⁹ The computation does not account for the resolution limit of e-beam lithography and lateral/longitudinal straggle of ion

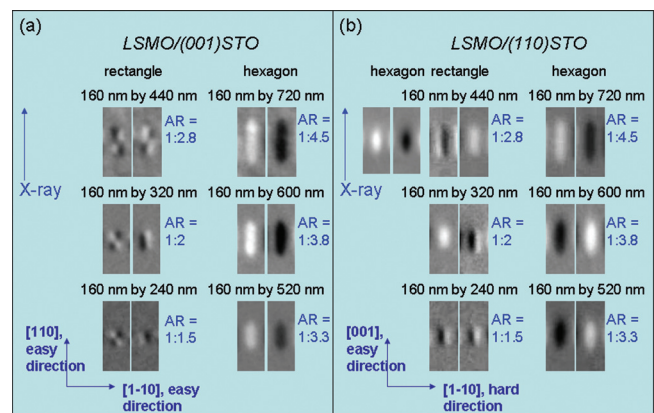


FIG. 2. (Color online) PEEM images of typical domain structures of (a) LSMO nanoislands prepared on (001)-oriented STO and (b) LSMO nanoislands prepared on (110)-oriented STO substrates, with rectangular shape for aspect ratios ranging from $1:1.5$ to $1:2.8$ and elongated hexagonal shape for aspect ratios ranging from $1:2.8$ to $1:4.5$. (Black and white contrast indicates oppositely magnetized domain states in a direction parallel to the incident x -ray direction.)

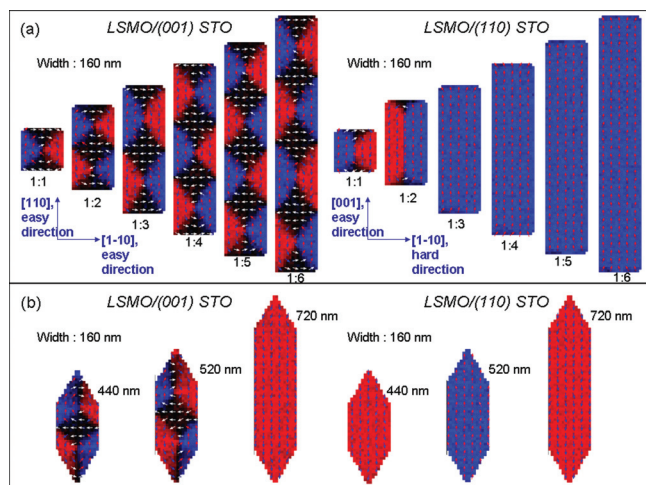


FIG. 3. (Color online) Theoretically predicted domain structures of (a) LSMO rectangular nanoislands and (b) LSMO elongated hexagonal nanoislands.

implantation resulting in rounded edges which could further modify the nucleation of domains at the ferromagnetic island/paramagnetic matrix interface.

In agreement with experiment, we have found that domain structures of (001)-oriented LSMO rectangular islands evolve from single flux-closed domain states to multiple flux-closed domain states as the aspect ratio increases from 1:1 to 1:6 as shown in Fig. 3(a). Here the domain structure is a competition between the four-fold magnetocrystalline anisotropy and the two-fold shape anisotropy. In contrast, (110)-oriented LSMO rectangular islands exhibit two domain states for aspect ratios smaller than 1:2 and single domain states for larger aspect ratios above 1:2 [Fig. 3(a)]. These simulations are consistent with the experimentally obtained domain images (Fig. 2) and the fact that uniaxial strain and shape anisotropies dominate over the magnetocrystalline anisotropy in (110)-oriented LSMO islands.

Simulations of elongated hexagonal islands show domain structures different from those observed for islands with rectangular shape. Domain structures of (001)-oriented LSMO hexagonal islands evolve from flux-closed four domain states to single domain states as shown in Fig. 3(b). However, (110)-oriented LSMO hexagonal islands exhibit only single domain states [Fig. 3(b)]. The (110) simulations are consistent with experimentally obtained single domain structures of elongated hexagonal islands where the tapered

edge appears to suppress the nucleation of domains. For (001) hexagonal islands, the discrepancies between theoretically predicted flux-closed four domain states and experimentally observed single domain states for aspect ratios smaller than 1:3.25 may be attributed to the 3-dimensionally rounded edges resulting from the ion implantation process.

IV. SUMMARY

In summary, we have fabricated LSMO rectangular and hexagonal islands with the smallest dimension of ~ 160 nm and observed the evolution of domain states by controlling their shape, aspect ratio and crystalline orientation. Both experimental results and OOMMF simulations show better performance of (110)-oriented LSMO elongated hexagonal islands in stabilizing single domain states, providing promise for applications to nanoscale spin-based devices.

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