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Evolution of Magnetic Domain Structure in a YIG Thin Film *

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The evolution of a magnetic domain structure induced by temperature and magnetic field is reported in silicon-doped yttrium iron garnet (YIG) films with perpendicular anisotropy. During a cooling-down procedure from 300 K to 7 K, a 20% change in the domain width is observed, with the long tails of the stripes being shortened and the twisting stripes being straightened. Under the influence of the stray field of a barium ferrite, the garnet presents an interesting domain structure, which shows an appearance of branching protrusions. The intrinsic mechanisms in these two processes are also discussed.

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Yttrium iron garnet (YIG) ferrite has attracted extensive attention due to its low damping parameter, low ferromagnetic resonance linewidth, moderate permeability, and large Faraday rotation, thus playing a crucial role in theoretical research and industry applications.[1,2] The diverse inhomogeneous domain structure is one of the most important research subjects. Understanding the mechanisms that allow for control of the domain structure may have far-reaching consequences for the development of data storage technology.[3] Magnetic domains of garnet films can be observed easily via magneto-optical microscope or magnetic force microscopy,[4,5] which commonly show a labyrinth structure.[6,7] However, other types of domain structures may also appear under the influence of a magnetic field,[8] which is an important factor in determining the domain structure. A series of rectangular field pulses applied to garnet films may lead to rotations of ring-shaped domains,[9] and bubble domains may emerge when the magnetic field is slightly tilted away from the easy direction of garnet films with in-plane anisotropy.[10] Temperature also affects the formation and evolution of magnetic domains.[11,12] However, the dominant mechanisms are different in these two domain structure evolutions (induced by magnetic field or temperature), as discussed in the following.

In this Letter, we present two evolution processes of the domain structure of a garnet film. The influence of temperature on the domain structure is performed via an optical cryostat, which is cooled by a continuous flow of liquid helium with tunable temperature from 300 K to 7 K.[13] The second process uses the stray field of a barium ferrite to induce domain structure evolution. Domain structures of the barium ferrite is observed via the magneto-optical indicator film (MOIF) technique.[14] An iron garnet is laid on top of the non-transparent magnetic sample, the stray field of which induces a spin rotation in the garnet film. Hence, the domain of the sample is observed through the magneto-optic Faraday effect created in the garnet film. The MOIF technique reveals visual magnetization reversal processes and domain structures of hard magnetic or recording materials.

The experiments are performed on a silicon-doped 12-μm-thick YIG film with perpendicular anisotropy, which is grown on the surface of a gadolinium gallium garnet substrate by pulsed laser deposition. The substitution of quadrivalent silicon creates divalent ions in the YIG, which supports simple domain structures determined by magneto-crystalline anisotropy and magnetostatic effects.[15]

A transmission magneto-optical microscope is used to image the domain structure in the study of the influence of temperature on the magnetic domain structure, due to the fact that the transparent YIG film exhibits a large Faraday rotation. The microscope is equipped with halogen lamps, a circular aperture, and spectral filters to select the yellow light as the light source. When the analyzer deviates slightly from the extinction position, high-contrast domain images are recorded by a charge-coupled device camera. The resolution of the microscope is in a micron range. Meanwhile, the domain structure evolution of the sample under the influence of the stray field of $BaFe_{12}O_{19}$ ferrite is performed with a reflection magneto-optical

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microscope; only the Kerr effect is available due to the fact that the barium ferrite is non-transparent. Barium ferrite is a high-coercivity magnetic material.[16] Its domain structures cannot be observed directly by a magneto-optical microscope in visible light bands, while they can be imaged indirectly via the MOIF technique. The reflection magneto-optical microscope is equipped with double sample holders, as shown in Fig. 1. The YIG film and the 0.6 mm barium ferrite are placed on the upper and lower sample holders separately. The lower holder can be adjusted accurately by a height control knob with micron resolution. The upper thin holder has a central hole to allow the two samples to reach each other closely.

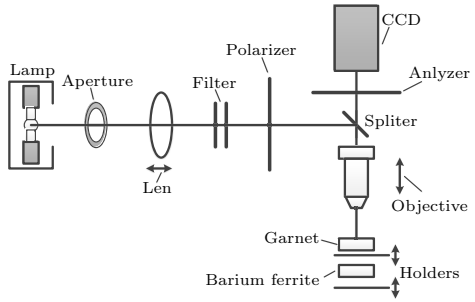

Fig. 1. Schematics of the reflection magneto-optical microscope.

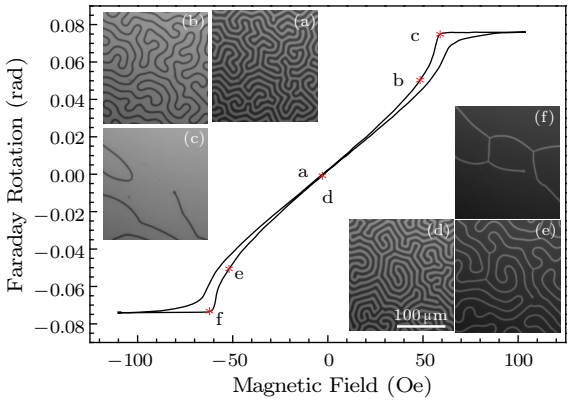

Fig. 2. Out-of-plane Faraday loop of the YIG film is measured with a 0.6 Hz alternating magnetic field. Inset: (a)–(c) and (d)–(f) are the domain structure evolutions with the application of the increasing positive magnetic and negative magnetic fields, respectively.

The perpendicular saturation field of the YIG film is approximately 80 Oe at room temperature (Fig. 2). The Faraday rotation reaches up to 0.074 rad at $\lambda = 632.8$ nm, thereby producing high-contrast domain images. The YIG exhibits no hysteresis at the field $H < 25$ Oe. The magnetic hysteresis behavior is observed only at the magnetic field above 25 Oe. From the domain structure perspective, the domain structure of the YIG is labyrinth at zero fields. As is shown in Fig. 2(a) and Fig. 2(d), different magnetization states in the image are indicated as bright (spin-up) and dark (spin-down) contrasts. The spin-up region expands with the application of an increasing positive magnetic field (Figs. 2(a)–2(c)), while the spin-down region expands with the application of an increasing negative magnetic field (Figs. 2(d)–2(f)) through domain wall motion until the sample is magnetized entirely at the saturation field.

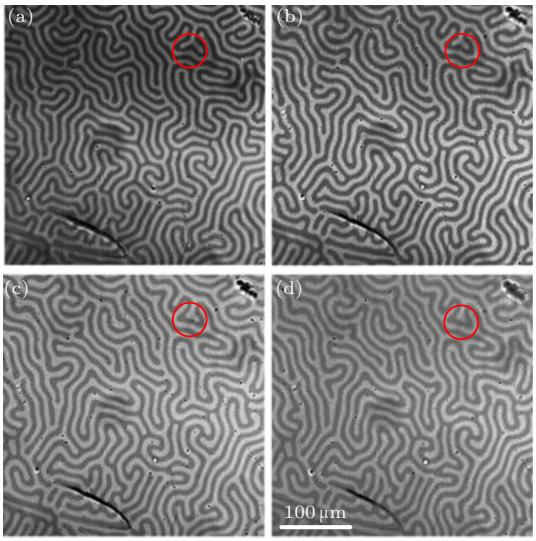

Fig. 3. Evolution of the domain structure during the cooling-down procedure: (a) 300 K, (b) 140 K, (c) 63 K, and (d) 7 K.

The evolution of the domain structure is studied during the cooling process. The sample is located in an optical cryostat. Firstly, the thin film is magnetized with a sufficiently strong magnetic field (above saturation field 80 Oe) via an electromagnet supplied with a direct-current power. Then, the field is released. Afterwards, the thin film is cooled down from 300 K to 7 K, and its magnetic domain structure at different temperatures is observed without any applied magnetic field during the cooling procedure. At room temperature, the domain structure of the thin film is the standard labyrinth, as shown in Fig. 3(a). During the cooling-down procedure, the main topological structure of the magnetic domain does not change considerably. Locally, the domain wall moves slightly and slowly. The domain structure has long tails at room temperature. As the temperature goes down, the tails become shorter, and the twisting stripes tend to straighten (see regions of red circles in Figs. 3(a)–3(d), with the temperature being 300, 140, 63 and 7 K, respectively). The period of domain structures, which is twice the width of the stripe domain, is 10 μm at room temperature and increases by 20% when the temperature falls from 300 K to 7 K. This evolution of the domain structure is dominated by magnetostrictive interaction. The YIG is a high-magnetostriction material, and the magnetostriction interaction is temperature dependent. At a lower temperature, the magnetostrictive interaction takes effect, thus shortening the long tails and straightening the twisting stripes.

Therefore, the total length of the domain wall becomes shorter, and the domain wall energy reduces.

In contrast with temperature, the magnetic field usually induces a significant change of the domain structure. The basal domain of the $BaFe_{12}O_{19}$ ferrite is observed (Fig. 4(a)) when the YIG is laid closely on the $BaFe_{12}O_{19}$ ferrite. The period of stripe domain of the $BaFe_{12}O_{19}$ ferrite is 40 μm, which is considerably different from the 10 μm period domain of the YIG film. The domain structure evolves as the lower holder is regulated to increase the distance between the YIG and the barium ferrites, as shown in Figs. 4(a)–4(c). Every protrusion of the basal domain grows into two branches and lengthens. Meanwhile, the basal domains shrink and become narrow. When the distance between the YIG and the barium ferrites is beyond 40 μm, the domain structure is steady, thereby indicating that the stray field of the barium ferrite does not influence the YIG anymore. Finally, the domain period goes back to 10 μm again. Under the influence of the stray field of the barium ferrite, interesting branching domains are observed. After the removal of the barium ferrite, the remanent state is modified instead of reconstructing its labyrinth domain, which is the remanent domain after the magnetic field reduces from saturation field to zero, and a branching domain structure is formed in the YIG, which shows an appearance of branching protrusions.

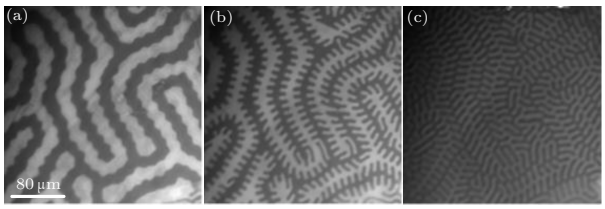

Fig. 4. With the use of the MOIF technique, the basal domain in BaFe12O19 ferrite is visible, the period is 40 μm. (a) The branching domain structure in garnet is observed by the removal of the $BaFe_{12}O_{19}$ ferrite, while the domain period is still 10 μm. (b, c) The domain structure evolution processes.

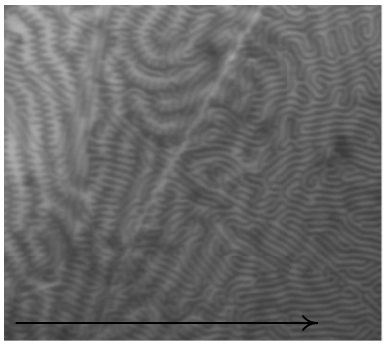

Fig. 5. Double-layer domain structure. The left part shows a branching domain structure. The right part shows a two-layer structure, with the arrow indicating a slow transition between these two regions. The bottom (top) layer shows the wider basal domain of the $BaFe_{12}O_{19}$ ferrite (the labyrinth domain of the YIG) on the right.

The branching domain has ever been observed in the cobalt crystal, and the degree of branching increases with increasing the sample thickness, which is caused by a kind of hybrid following the high-anisotropy two-phase branching scheme in the bulk and low-anisotropy multiaxial branching scheme at the surface.[10] The branching domain in the YIG is speculated to be a kind of hybrid, with the 40 μm period basal domain in the bulk, and the 10 μm period domain on the surface. The interior of the bulk possesses high uniaxial anisotropy, and the basal domain of $BaFe_{12}O_{19}$ ferrite is retained, while the YIG reconstructs the labyrinth domain only at the low-anisotropy surface, where the domain wall energy and the stray field energy are smaller.

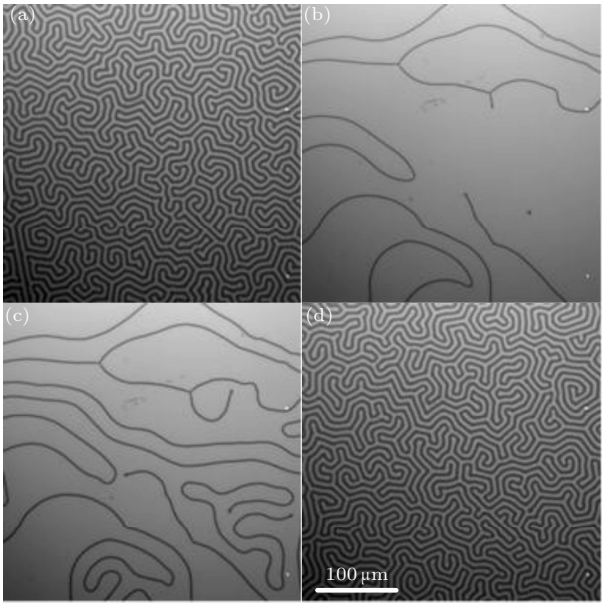

Fig. 6. Reconstruction of the domain structure in the YIG garnet under the influence of an external magnetic field. Initial state (a) at 0 Oe and (b) at the near-saturation field; (c) nucleation starting from the saturation; and (d) at remanence.

The following experiment proves the existence of the double-layer domain structure. The domain of the YIG is recorded when it makes contact with rough $BaFe_{12}O_{19}$ ferrite, as shown in Fig. 5. The left part of Fig. 5 shows a branching domain structure. The right part shows a two-layer structure, with the arrow indicating a slow transition between these two regions. The bottom (top) layer shows the wider basal domain of the $BaFe_{12}O_{19}$ ferrite (the labyrinth domain of the YIG) on the right of Fig. 5. Figure 6 shows the domain reconstruction process of the YIG. When the external magnetic field drops from the saturation field, the domain structure evolves, as shown in Figs. 6(b)–6(d). The YIG then reconstructs the labyrinth domain structure starting from some random nucleation centers. If the magnetic field is not strong enough to

magnetize the YIG, then the remanent position becomes fixed nucleation centers. The domain wall then moves until the stripes recover their original width (Fig. 6(d)). However, the remanent domain structures are different from those before the magnetic fields are applied.

In conclusion, the evolution process of the domain structure of the YIG has been studied during the cooling-down procedure from 300 K to 7 K at zero magnetic field. As the temperature goes down, the width of the stripes of the labyrinth domain is broadened by shortening the long tails of the stripes and by straightening the twisting stripes. Such small changes are dominated by magnetostriction anisotropy. However, the magnetic field induces a major transformation of the domain structure. Under the influence of barium ferrite, a branching domain structure is observed in the YIG. The basal domain of the $BaFe_{12}O_{19}$ ferrite is retained in the bulk of the YIG, and the YIG reconstructs its labyrinth domain at the surface only. Such a difference arises from axial anisotropy.

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