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Magneto-optic study of the behavior of magnetic domains walls in ferrimagnetic garnet films placed over samples with in-plane magnetization

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ABSTRACT

Magneto-optic (MO) imaging is based on Faraday rotation of a linearly polarized incident light beam illuminating a sensitive MO layer placed in close contact to the sample. For in-plane magnetized layers of $Lu_{3-x}Bi_x Fe_{5-y}Ga_yO_{12}$ ferrimagnetic garnet films, zig-zag domain formation occurs whenever the sample stray parallel field component changes sign. In this work we study the behavior of zig-zag domain walls that appear when the garnet is placed over samples with in-plane magnetization like audio tapes recorded with different signals. We describe the zig-zag walls considering the anisotropy, exchange and magnetostatic energies in the Neel tails and the contribution of an applied magnetic field. Using different recorded signals we have been able to control the gradient of stray parallel field component on the garnet, changing the distance between domains and the size of zig-zag walls. We could even avoid the appearance of these zig-zag domain walls and obtain closed domains structures. We also study the behavior of the domain walls when an external magnetic field is applied parallel to the sample.

1. Introduction

Magneto-optical (MO) imaging provides a powerful tool for the direct observation of magnetic flux distributions. The method combines relatively high spatial resolution ($\sim 1\ \mu m$) and magnetic sensitivity (~ 0.2 G) with short measuring times ($< \mu s$) and large imaging areas (up to $10 \times 10\ mm^2$) [1].

This technique is based on the Faraday rotation of a linearly polarized light beam illuminating an MO layer (MOL) placed directly on top of the sample surface. The light passes through the layer, is reflected at a thin mirror coating deposited on its back face, and passes a second time through the sensitive film, thus doubling the Faraday rotation angle, θ_F. For normal light incidence, the rotation angle grows with the magnitude of the local perpendicular magnetic field. By using another polarizer in an optical microscope, one can directly visualize and quantify the field distribution across the sample area. Active layers with in-plane easy magnetization direction [2] have significantly improved the MO imaging technique [3].

Zig-zag domain formation occurs in the MOL when the sample stray parallel field component ($\boldsymbol{H}_y$) changes sign. In each domain the MOL magnetization $\boldsymbol{M}_s$ points in the direction of the parallel field component, $\boldsymbol{H}_y$, generated by the sample bellow the MOL. These domains appear superimposed on the image of the sample's normal field component ($\boldsymbol{H}_z$).

In this work we study the behavior of zig-zag domain walls that appear when the garnet is placed over samples with in-plane magnetization. To do this it is necessary to control the parallel field component at the MOL plane, and particularly its change in sign. For this purpose, we have used periodically magnetized audio tapes as samples [4]. The tapes were magnetized using square audio wave forms of different frequencies, with the well-known tape recording technique [5]. The tape stray magnetic field components have been calculated analytically elsewhere [6], at the MOL location. Images were obtained for tapes magnetized at different frequencies and the evolution of domain walls is investigated. We also study the behavior of the domain walls when an external magnetic field is applied parallel to the sample.

The paper is organized as follows. Section 2 describes the experimental array. The formation of domain walls and the calculated magnetic fields are presented in Section 3. Results and discussion are addressed in Section 4.

2. Experimental

The recorded signal is a direct spatial reproduction of the original temporal signal. Square wave functions were computer generated and recorded on commercial audio tapes. We used different frequencies audio signals with tapes with linear velocity $v = 47.5$ mm/s.

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The MOL we have used in the present work is a Bi-doped garnet film, $Lu_{3-x}Bi_x\ Fe_{5-y}Ga_yO_{12}$ with in-plane magnetization [7]. The indicator film was deposited to a thickness of 4.5 mm by liquid-phase epitaxial growth on the (1 0 0) oriented gadolinium gallium garnet substrate. A thin ($\sim$120 nm) Au layer was evaporated onto the film in order to reflect the incident light and thus to provide a double Faraday rotation of the light beam. To image each sample, the pair polarizer analyzer was set slightly out of crossing so that perpendicular fields of opposite polarity were distinguished in the MO image, i.e., a medium gray color represents zero field. This angle was fixed to $\theta_0 = 4^\circ \pm 10\%$ for all samples. The air gap between the sample and the MOL indicator was minimized. In the calculations, the finite distance between the sample surface and the MOL was taken into account, i.e., the magnetic field is calculated at a distance of $1/100\ l$, where l is modulation period.

A standard Olympus BX60M microscope was used with 20X magnification, and a Roper Scientific CoolSnap CF camera recorded the images, which were transferred to a computer for processing.

3. Modeling

The tape was modeled as an infinite strip of width $-w/2 \le x \le w/2$ and thickness $-s/2 \le z \le s/2$ (see inset in Fig. 1) where the in-plane magnetization is $\boldsymbol{M}_y(y)$.

We will take the limit $s=0$. To calculate $\boldsymbol{H}$ at the sensitive layer location, we made use of the Maxwell equation for a source with magnetization and without free current: $\nabla.\ \boldsymbol{H}=0$ and $\nabla \times \boldsymbol{H} = -4\pi\nabla.\ \boldsymbol{M}$. The tape magnetization $\boldsymbol{M}=\boldsymbol{M}_y(y)$ was assumed periodic with period l, with amplitude m_0 and a square waveform is examined. Calculating in the usual way, the volumetric charge density related to the magnetization variation, and as source of the magnetic potential, ϕ_M. The field $\boldsymbol{H}$ is given by $\boldsymbol{H} = -\nabla\phi_M$. One arrives at the results plotted in Fig. 1 for magnetic fields components, $\boldsymbol{H}_z$ (panel b) and $\boldsymbol{H}_y$ (panel c), perpendicular and parallel to the strip, respectively [6].

In the present work, we will refer to the role of the gradient of the $\boldsymbol{H}_y$ generated by the magnetic tape in the behavior of domain walls in the MOL.

4. Results and discussion

In a previous work [8] we have described the zig-zag walls considering the anisotropy, exchange and magnetostatic energies in the Neel tails and the contribution of the magnetic field of the tape. We have showed that the size of the domain walls decreased as a function of the gradient of the stray parallel field component ($\boldsymbol{H}_y$) on the MOL.

In this work we have used different frequencies on the recorded signal to control this gradient, changing the distance between domains and the size of zig-zag walls. We could even avoid the appearance of these zig-zag domain walls and obtain closed domains structures. In Fig. 2 we show this dependence with the frequency of the recorded signal.

At low external fields (f=500, 1000 Hz) the Zeeman energy term for a perpendicular magnetization of the indicator with respect to the stray field produced by the tape gives place to the formation of zig-zag Neel walls,

$$E_H = -J_s \int \boldsymbol{H}_{ex}\boldsymbol{m}dV$$

with J_s the saturation magnetization of the MOL. But for greater external fields (f=2000 Hz when closed domains appear), the reduction of energy coming from a Neel wall is lower than the reduction in the Zeeman energy if the MOL magnetization turns over from one domain the other rotating outside the indicator plane thus generating a Bloch wall.

With this MO technique is easy to recognize between these two types of walls because in the case of a Bloch wall, the perpendicular magnetization is the one that produces the rotation in the polarized light, giving a lighter or darker zone along the Bloch wall in contrast with the intensity uniform Neels wall. This can be seen in Fig. 3(a) in the MOL recorded at f=2000 Hz. In Fig. 3(b) we show a sketch of the magnetization around one closed domain indicating the Bloch and Neel walls.

If the frequency (i.e. the gradient of $\boldsymbol{H}_y$) is further increased even when the closed domains disappear. An intensity modulation over the MO pattern, can be observed. Fig. 4(a) show a tape recorded with f=5000 Hz where there are not closed domains or zig-zag walls anymore. The horizontal light intensity profile is shown in panel (b). Minima (dark stripes marked 2, 4, 6, 10) and maxima (clear stripes 1, 5, 7, 9) are indicated in both panels. The magnetization of the garnet shows this modulation that arises from the perpendicular magnetic field from the tape and reverses its direction at the Bloch walls marked at 3 and 8. A sketch of the orientation of the magnetization and its relation with the maxima, minima and Bloch walls is shown in panel (c).

A similar effect can be shown when we applied an external field provided by an electromagnet, parallel to the surface of the sample, controlling in this way the gradient of $\boldsymbol{H}_y$. Fig. 5 shows

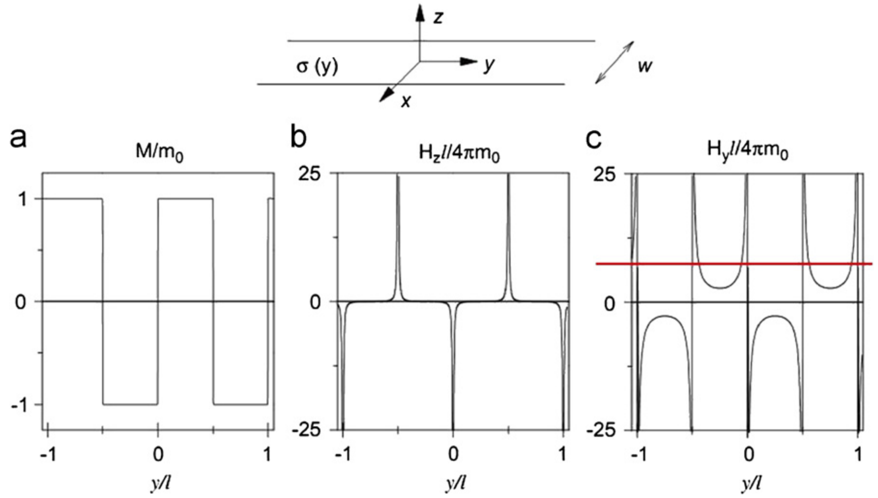

Fig. 1. *Inset*: tape geometry strip of width w with in-plane magnetization dependent on coordinate y: (a) square waveform tape magnetization $\boldsymbol{M}_y(y)$; (b) $\boldsymbol{H}_z$ component and (c) $\boldsymbol{H}_y$ field component generated by the tape at the MOL plane.

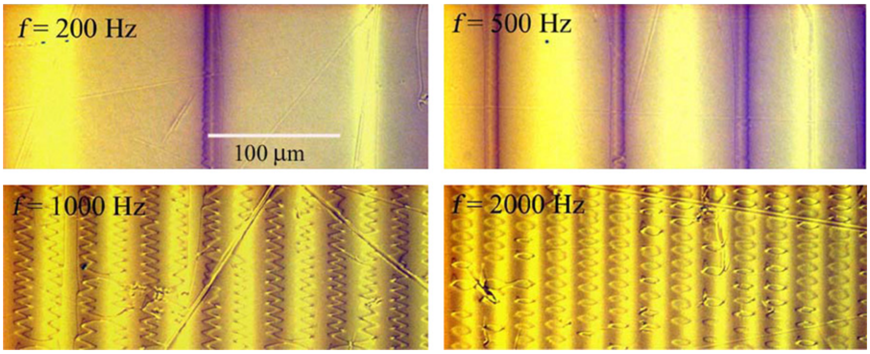

Fig. 2. Domain formation on MOL placed over square wave form tape at different frequencies. Zig-zag walls can be seen up to $f=1000$ Hz. At $f=2000$ Hz closed domains appear.

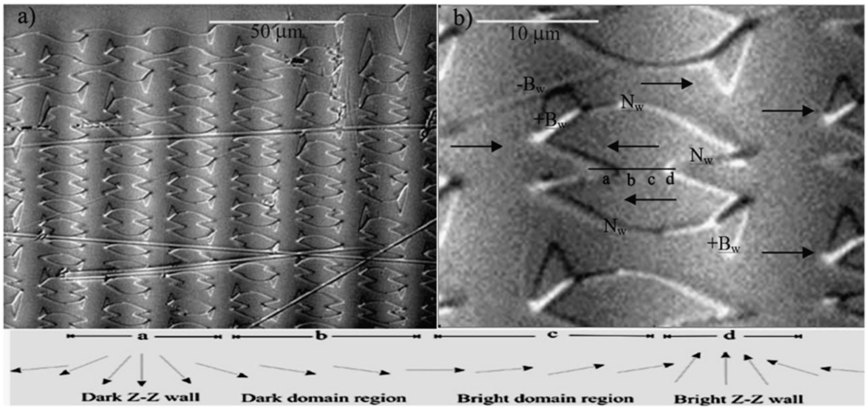

Fig. 3. Left panel: closed domains in MOL over a tape recorded with $f=2000$ Hz squared wave. Right panel: detailed magnetization in a closed domain showed schematically. Bright-dark domain walls are Bloch walls ($+B_w$, $-B_w$) where magnetizations rotates out of the field increasing the magneto optic effect. Other walls are Neel walls (N_w) where the magnetization change direction rotating in the plane.

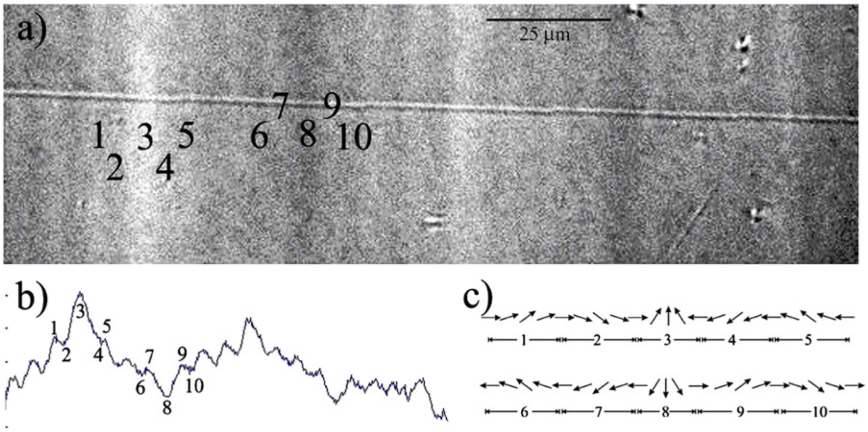

Fig. 4. (a) Image of a MOL over a tape recorded with $f=5000$ Hz squared wave. (b) Profile of light intensity across the sample in the horizontal direction. (c) Magnetization of the MOL showed schematically. Intense bright-dark patterns are Bloch walls ($+B_w, -B_w$) where magnetizations rotates out of the plane (3,8). Other bright-dark patterns (maxima–minima) are MO effects associated with $\boldsymbol{H}_z$ field from tape.

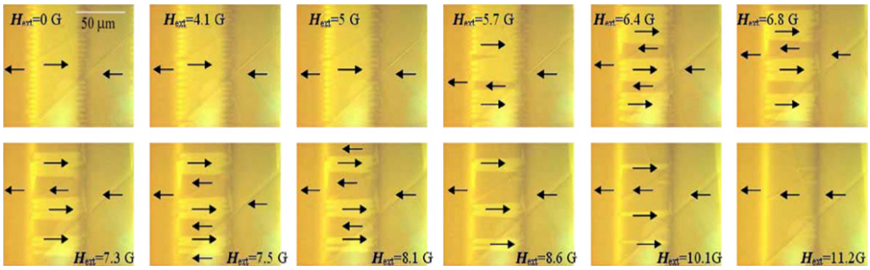

Fig. 5. Effect of applying an external magnetic field $\boldsymbol{H}_{ext}$ parallel to the MOL surface on a sample recorded with $f=500$ Hz square wave. Zig-zag domain walls separates region of the sample with different magnetizations. As $\boldsymbol{H}_{ext}$ is increases zig-zag walls form closed domains and disappear.

how the regions with one direction of magnetization began to grow and the ziz-zag walls grow and surround these regions with opposite magnetization orientations as the H_{ext} is increased. This applied field does not alter the perpendicular field that generally is observed with this technique as the clear and dark fringes are not perturbed.

Zig-zag walls and closed domains in the MOL, are related with the parallel stray field of the sample under study, generate noise in the measured profiles corresponding to the sample magnetization. We showed that applying an external parallel magnetic field reduce this noise because of the rearrangement in the MOL magnetization orientation, eliminating the zig-zag walls.

Acknowledgement

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