Imaging of domain wall motion in small magnetic particles through near-field microscopy

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We report magneto-optical scanning near-field optical microscopy images for \( 4 \times 4 \times 0.08 \) \( \mu \)m\(^3\) and \( 16 \times 16 \times 0.08 \) \( \mu \)m\(^3\) low magnetic anisotropy \( \text{Co}_{70.4} \text{Fe}_{4.6} \text{Si}_{15} \text{B}_{10} \) particles. Measuring magneto-optical differential susceptibility we acquired images of the domain wall movement driven by an applied magnetic field with a spatial resolution better than \( \lambda/4 \). For the \( 4 \times 4 \times 0.08 \) \( \mu \)m\(^3\) sized particle, a sequence of 27 magneto-optical differential susceptibility images reveals the evolution of the magnetic domain structure between positive and negative saturation fields passing through the four-domain flux-closure magnetization structure. On the \( 16 \times 16 \times 0.08 \) \( \mu \)m\(^3\) particle, we studied the role of the oscillating driving field on the susceptibility distribution. Comparing the different magneto-optical differential susceptibility sequences, the role of the shape anisotropy on the field induced domain wall movement is evidenced. Micromagnetic simulations were used to provide a better understanding of the domain wall movement. © 2006 American Institute of Physics. [DOI: 10.1063/1.2172016]

The deep understanding of magnetic properties of domains and domain walls is of crucial importance to the development of magnetic devices on the nanosize scale. Besides established magnetic microscopies such as magnetic force microscopy (MFM) or scanning electron microscopy with polarization analysis (SEMPA), much effort has been made to obtain instrumentation capable of easily studying ac and dc magnetic field induced processes at high resolution. Since the pioneering work of Betzig and co-workers,\(^1\) some reports have shown the importance of the magneto-optical scanning near-field optical microscopy (MO-SNOM) achieving high resolution and sensitivity.\(^2,3\) Being sensitive to magneto-optical Kerr effects, MO-SNOM measurements fundamentally deal with scattered light, being insensitive to external magnetic field. Nevertheless, due to the lack of systematic results reported so far in the literature, the MO-SNOM technique is not yet an established tool to study thin magnetic films and small magnetic particles. In this letter we propose and demonstrate the usefulness of the MO-SNOM to the systematic study of the magnetic domain patterning and its dynamics for micron-sized magnetic particles.

The MO-SNOM set-up operates like a tuning fork AFM in the shear-force mode, and has the possibility of optical measurements in reflection illuminating mode (\( \lambda =670 \) nm). The applied magnetic field is perpendicular to the plane defined by the tip, light detector and the measured position on the sample surface; such a configuration corresponds to the well known far-field transverse magneto-optical Kerr effect (TMOKE). The experimental set-up is able to acquire topographic, optical and magneto-optical images. Moreover, the tip can be adjusted at any position on the sample surface, allowing the acquisition of local hysteresis loops.\(^4,5\) The tip is a metallized tapered optical fiber operating at \( \sim \lambda/60 \) from the sample surface, which determines the near-field optical configuration. Under these conditions, the Rayleigh criterion is no longer a limitation and the acquisition of susceptibility images and hysteresis loops with a lateral resolution of \( \lambda/4 \) were obtained. The development of the experimental set-up and the measurement procedures were described elsewhere.\(^3\)

Isolated square \( \text{Co}_{70.4} \text{Fe}_{4.6} \text{Si}_{15} \text{B}_{10} \) particles with lateral dimensions of 4 and 16 \( \mu \)m and thickness of 80 nm were studied. The sample preparation was based on PMMA e-beam resist mask, sputtering deposition and lift-off process. During the film deposition the Si substrate was kept at liquid \( \text{N}_2 \) temperature to ensure an amorphous film with very low magnetocrystalline anisotropy and magnetostriction.

Figures 1(a) and 1(b) show the topographic (3D) and optical (2D) images acquired simultaneously for a \( 4 \times 4 \times 0.08 \) \( \mu \)m\(^3\) particle. On the optical image, along the upper particle edge, one can see a high intensity stripe. Although this kind of effect is common in optical SNOM images, the physical origin of the enhanced signal is not completely known yet. High intensity stripes are usually observed in structured metallic samples and their orientation depends on the polarization of light.\(^6\)

Instead of directly measuring the magnetization contrast, our approach was based on magnetic susceptibility measure-
ments, providing an important increase in sensitivity basically due to the use of lock-in amplifier detection. The magneto-optical differential susceptibility (MODS) image is a point by point evaluation of the local magnetic susceptibility under a weak oscillating magnetic field $H_{ac}$. Such an approach allowed overcoming both the long time relaxation features that usually drift off the magneto-optical contrast during the scanning process and the optical artifacts produced by roughness and heterogeneity of the sample surface.

In a microscopic particle with low magnetic anisotropy, the domain configuration is mainly determined by its shape anisotropy. For instance, when a $4 \times 4 \times 0.08 \, \mu m^3$ particle is submitted to a rather low intensity bias magnetic field $H_{bias}$, the shape anisotropy determines the four-domain flux-closure structure [as sketched in Fig. 2(a)] as the minimum energy state. In the MODS imaging the contrast detected at any sample position is proportional to the magnetization changing at this position due to the presence of $H_{ac}$. Figure 2(b) shows a sketch of the MODS image related to the particle in Fig. 2(a). The higher contrast is originated from the movement of the $180^\circ$ domain wall. In a similar way, extending from the high contrast area to the corners, one has an intermediate intensity contrast due to the field induced movement of the modified $90^\circ$ domain walls. Notice that the differential susceptibility is more intense around the domain wall than inside the domains since magnetic moments in the walls are more sensitive to the field than moments in the domains.

Figure 3 shows 9 of the 27 MODS images sequentially acquired on a $4 \times 4 \times 0.08 \, \mu m^3$ particle in the presence of different $H_{bias}$. We applied a sinusoidal magnetic field ($H_{ac}$) with amplitude and frequency equal to 11 Oe and 155 Hz, respectively, superposed to $H_{bias}$ in the same direction as indicated in Fig. 2(b). Despite the rather large topographic step (80 nm), the particle boundaries give low contrast in all MODS images. On the other hand, a stripe parallel to the upper particle edge, remaining from the high intensity stripe observed in the optical image [Fig. 1(b)], can also be seen in all MODS images of Fig. 3, revealing a small cross-talk between optical features and MODS contrast.

For $H_{bias} = -50$ Oe [Fig. 3(a)] the MODS image presents two regions of higher intensity [dashed circles in Fig. 3(a)].

Due to the simultaneous action of $H_{bias}$ and $H_{ac}$ ($-50$ and 11 Oe) during the image acquisition, the magnetic pattern oscillates between the magnetic saturation and an asymmetric four-domain flux-closure structure. Actually, the starting configuration is not fully saturated but the field is high enough to remove the asymmetric flux-closure domain. The two high susceptibility regions are related to the nucleation of two degenerated four-domain flux-closure structures with opposite chiralities. Slightly decreasing the $H_{bias}$ to $-44.5$ Oe [Fig. 3(b)] only the clockwise chirality of the domain structure remains. Continuing to decrease the $H_{bias}$ to $-28$ Oe [Fig. 3(c)] the domain located on the bottom of the particle is still favored, and the $180^\circ$ domain wall is situated close to the upper edge of the particle. Applying now a slight positive bias field ($H_{bias} = 22$ Oe), the particle exhibits nearly no net magnetization [Fig. 3(e)]. Increasing $H_{bias}$ to 44.5 Oe [Fig. 3(f)], and even further to 61 Oe [Fig. 3(g)], the upper domain is favored, leading the $180^\circ$ domain wall contrast region to move towards the bottom edge. In Fig. 3, one can note how the susceptibility distribution can be highly dependent on the bias field. For $H_{bias}$ equal to 61 Oe the patterning presents only one region of high contrast whereas for 66.5 Oe [Fig. 3(g)], the central spot separates into two spots that move to the bottom corners.

In order to better understand the nature and movement of domain walls we have performed micromagnetic simulations based on the Landau-Lifshitz-Gilbert equation using the object oriented micromagnetic framework (OOMMF) program. We have simulated the magnetic domain structures for a $4 \times 4 \times 0.08 \, \mu m^3$ size particle using a unit cell size of $20 \times 20 \times 20 \, nm^3$ and typical CoFeSiB magnetization of saturation ($640 \times 10^3 \, A/m$) and exchange stiffness constant (10 pJ/m). The experimental data are well fitted assuming a low value of magnetic anisotropy ($600 \, J/m^2$) parallel to the magnetic field. We utilized the program to perform susceptibility image simulation. To evaluate the magneto-optical pattern, only the transverse horizontal component of the magnetization was considered. A small $H_{ac}$ is added to the $H_{bias}$ to follow experimental conditions and the susceptibility pattern is obtained taking the difference between images corresponding to the minimum and maximum magnetic field values after two oscillations. Figure 4 shows simulation images.
for \(H_{ac} = 20\) Oe. Figure 4(a) and 4(b) shows the simulated magnetization and susceptibility images for \(H_{bias} = 20\) Oe. Notice that the simulated susceptibility pattern is highly similar to the experimental pattern [see for instance Fig. 3(e), \(H_{bias} = 22\) Oe].

In Fig. 4(c) and 4(d), \(H_{bias} = 140\) Oe was used. On the susceptibility image, two regions of high contrast are visible close to the bottom corners, resembling to Fig. 3(h) \((H_{bias} = 66.5\) Oe). Due to the topological freezing, the ac magnetic field \((H_{ac} = 20)\) Oe is not sufficient to move the 180° domain wall. The two regions of high contrast are related to the movement of the modified 90° domain walls that link the static 180° domain wall to the bottom corners. Thus, considering the experimental data of Fig. 3, we suppose that the four-domain flux-closure structure is still valid for \(H_{bias} = 66.5\) and 83 Oe. Moreover, we observed the nucleation field for the four-domain flux-closure pattern being equal to \(-44.5\) Oe and the zero magnetization condition for \(22\) Oe. This field asymmetry indicates a hysteretic magnetic behavior.

Regarding Figs. 3(c)–3(g) \((H_{bias} = -28\) to 61 Oe), we observed that the width of the high susceptibility contrast region is \(\approx 0.5\) μm. Thus, except when the topological freezing becomes significant, \(H_{bias}\) is not relevant to the determination of the 180° domain wall movement in such small particles. By contrast, when comparing to a larger particle size, it is worth noting how the topological freezing, being proportional to the shape anisotropy, is determinant on the field induced domain wall motion. In Fig. 5, we have experimental images of the susceptibility pattern for a 16×16 ×0.08 μm² particle for several values of \(H_{ac}\) at remanence. For \(H_{ac} = 1.3\) Oe [Fig. 5(a)], the movement of the 180° domain wall generates a thin stripe with moderate contrast. This contrast becomes higher for \(H_{ac} = 2.7\) Oe [Fig. 5(b)] reaching a saturation value for \(H_{ac} = 5.5\) Oe [Fig. 5(c)]. The susceptibility saturation signal ([Fig. 5(f)], around 1.2 mV) is related to the full 180° magnetization reversal. The small relative displacement of the large 180° domain wall explains why the saturation susceptibility contrast is not observed for \(H_{ac} = 1.3\) and 2.7 Oe. In Fig. 5(c), the overall features for a MODS image in a four-domain flux-closure pattern [see Fig. 2(b)] is observed. Notice the MODS pattern due to the 180° and 90° field induced domain wall movement, and even the low contrast due to the slight coherent spin rotation in the domains oriented perpendicular to \(H_{ac}\). For \(H_{ac} = 8.3\) and 11 Oe [Figs. 5(d) and 5(e)], the same susceptibility pattern is observed, but the larger intensity of the driving field increases the domain wall movements and the coherent spin rotations inside the domains. Using the same driving field of Fig. 3 \((H_{ac} = 11\) Oe) we observe in Fig. 5(e) a much wider domain wall movement. For instance, in the 16×16 ×0.08 μm² particle, the 180° domain wall displacement is around 13 times larger \((\approx 6.5\) μm) than for the 4×4 ×0.08 μm² particle. It is a clear evidence of the role of the shape anisotropy on the field induced magnetic behavior. The graphic in Fig. 5 shows the susceptibility profiles for each image taken along the position indicated by the dashed line on the first image. For \(H_{ac} = 1.3\) Oe, the susceptibility profile shows a narrow peak that presents an asymmetric shape probably related to the local magnetic anisotropy and defect distribution. As \(H_{ac}\) increases, low potential energy distribution becomes less relevant and the susceptibility profiles, apart from being broader, become more regular.

Summarizing, systematic sequences of MODS images were acquired for micron sized low magnetic anisotropy particles under the action of different external magnetic field conditions. Images suggest resolution better that 200 nm. The 27-image sequence reveals the susceptibility pattern’s evolution during magnetic reversal of a 4×4×0.08 μm³ particle. Despite the rather large unit cell used (5 times the exchange length for amorphous Co70.4Fe4.6Si15B10), the micromagnetic simulations presented good agreement with the observed images. Both experimental and simulated sequences bear witness to the role of topological freezing on the domain wall motion. The sequence of Fig. 5 showed the dependence of susceptibility distribution on \(H_{ac}\) in a 16×16×0.08 μm³ particle and, in comparison with the sequence of Fig. 3, showed the role of the shape anisotropy on the field induced domain wall motion. With the measured sequences, we demonstrate the usefulness of MO-SNOM to study field induced processes at submicroscopic resolution.

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