Unusual magnetization reversal in [Co/Pt]$_4$ multilayers with perpendicular anisotropy

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Unusual magnetization reversal of [Co(4 Å)/Pt(10 Å)]$_4$ multilayers with perpendicular magnetic anisotropy has been revealed macroscopically by magnetometry measurements and microscopically by magneto-optical Kerr effect microscopy and magnetic force microscopy (MFM) imaging. During the first-order reversal process, the magnetization first decreases, then reaches a plateau, and finally rises back to saturation, corresponding to expanding bubble domains, stationary domains, and fading contrast but unchanged boundary domains, respectively. MFM imaging reveals the existence of many submicron-scaled unreversed channels within the boundary of the "bubble" domains. The magnetization reversal behavior can be accounted for by the evolution of the unusual domain structures in different field regimes. © *2006 American Institute of Physics*.
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I. INTRODUCTION

Recently, [Co/Pt]$_n$ multilayers have been extensively studied because of the unique attribute of perpendicular magnetic anisotropy (PMA) and the potential applications in perpendicular magnetic recording.[1–10] The properties of [Co/Pt]$_n$ multilayers depend intricately on the number n of bilayer repeats. Many previous studies on these multilayers with larger values of $n(n>10)$ (Refs. 5–7) show that during magnetization reversal, the reversed domains nucleate from isolated defects and then develop into dendritic patterns. Magnetization reversal in the [Co(4 Å)/Pt(7 Å)]$_{50}$ multilayers has also been studied by the first-order reversal curve technique.[5] At the other extreme, thin Pt/Co/Pt trilayers revealed very different behaviors, where magnetic domains expand by the propagation of smooth and well-defined domain walls.[8,9] Under a reversed field, the domain walls retract toward the nucleation centers. However, there has been little work on [Co/Pt]$_n$ multilayers with an intermediate n, although several papers reported other materials with PMA and intermediate thickness.[11–13]

In this work, we have studied in detail the magnetization reversal behavior of [Co(4 Å)/Pt(10 Å)]$_4$ multilayers with an intermediate $n=4$, and revealed very unusual reversal behavior. The reversal has been studied macroscopically by vibrating-sample magnetometry (VSM), and microscopically by both magneto-optical Kerr effect (MOKE) microscopy[9,14,15] and magnetic force microscopy (MFM) imaging.[7,10] The first-order reversal curves (FORCs) for [Co/Pt]$_n$ multilayers with an intermediate repeat number $n=4$ are very different from those for [Co(4 Å)/Pt(7 Å)]$_{50}$ multilayers.[5] The unusual magnetization reversal behavior can be explained by the evolution of the domain structure in different external field regimes, as confirmed by the direct domain observations by MOKE and MFM.

II. EXPERIMENT

The Pt(100 Å)/[Co(4 Å)/Pt(10 Å)]$_4$/Pt(20 Å) multilayers were deposited on silicon substrates by dc magnetron sputtering. The multilayer structures were verified by small-angle x-ray reflectivity measurements using a four-circle x-ray diffractometer (Philips X'Pert-MRD) with Cu $K\alpha$ ($\lambda=1.5405$ Å) radiation.[16]

Macroscopic magnetic properties were measured by a VSM with the magnetic field applied perpendicular to the film plane. Direct observation of the domain pattern evolution during the FORC procedure was made by MOKE imaging under an external field. To study the domain pattern on a submicron scale, MFM imaging was performed using a Veeco multimode MFM (Ref. 16) on the sample initially magnetized to the desired magnetic state by an electromagnet. Careful preexamination showed that the MFM tip did not alter the magnetic patterns of the sample.

III. RESULTS AND DISCUSSION

The small-angle x-ray reflectivity of the [Co/Pt]$_4$ multilayer (Fig. 1) confirmed the specifically designed multilayer structure. The periodicity of peaks at small angles reflects the overall thickness, 170 Å, of the deposited Pt(100 Å)/[Co(4 Å)/Pt(10 Å)]$_4$/Pt(20 Å), which agrees with the expected thickness of 176 Å.

The [Co/Pt] multilayers are among the few materials with well-established PMA.[17] The [Co/Pt]$_4$ multilayers used

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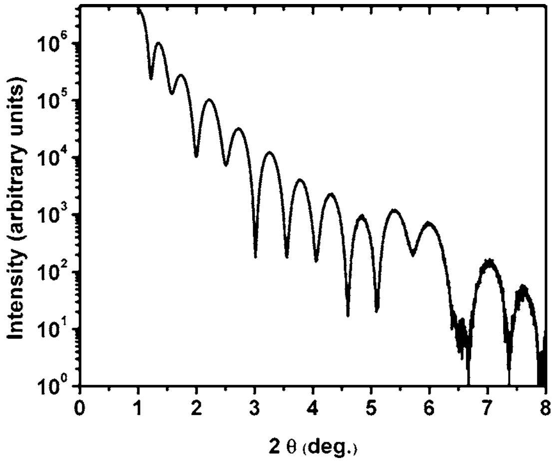

FIG. 1. Small-angle x-ray reflectivity data for [Co(4 Å)Pt(10 Å)]$_4$ showing that the overall thickness of 170 Å is in agreement with the designed structure.

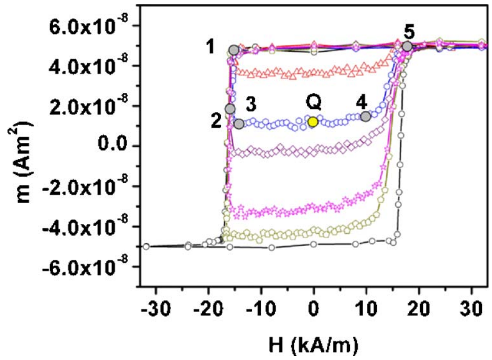

FIG. 2. Major magnetic hysteresis loop and several first-order reversal curves for a [Co(4 Å)Pt(10 Å)]$_4$ sample with returning fields of 15.1, 15.5, 15.9, 16.2, and 16.7 kA/m. Reference points 1–5 and Q mark the conditions where MOKE and MFM observations were performed.

in this work also exhibit PMA. A square hysteresis loop with sharp reversal was observed in [Co(4 Å)/Pt(10 Å)]$_4$ with a coercivity H_C=16.4 kA/m, as shown in Fig. 2. To reveal the details of the reversal process, we resorted to the method of FORC measurements, where the field was decreased from a positive saturation field to a negative field defined as the returning field $-H_T$ (H_T is the magnitude of the returning field), and then increased to the original positive saturation field.

Several FORCs for the [Co/Pt]$_4$ sample shown in Fig. 2 share common features, represented by the one with H_T =15.5 kA/m. Five numbered reference points are marked on the FORC with H_T=15.5 kA/m, as illustrated in Fig. 2. As H is decreased from the positive saturation field to $-H_T$, the magnetization (M) begins to decrease at a nucleation field (point 1) and continues to decrease to point 2. As H is now increased, M first decreases precipitously (between points 2 and 3), then reaches a plateau (between points 3 and 4), and finally increases towards the saturation value (between points 4 and 5). In contrast, in most FORC studies of magnetic thin films, including those of [Co/Pt]$_n$ multilayers with large n,[5] M rises with increasing H from the returning field $-H_T$.

To understand the unusual macroscopic FORC behavior, MOKE imaging of microscopic domain was performed in the external field following the same procedure as that for the marked FORC. Eight representative images, shown in Fig. 3, are closely related to the five reference points in Fig. 2: Images a–d were taken between points 1 and 2 in Fig. 2, image e was taken at point 3 but represents the domain pattern between points 3 and 4, and images f–h were taken between points 4 and 5.

Between points 1 and 2, the reversed domains (the dark area in Fig. 3) first nucleated from a few sites within the view [Fig. 3(a)]. The domains then grew in size with the outer boundary expanding to form larger reversed "bubbles" [Figs. 3(a)–3(d)]. This domain aspect is similar to the reversed bubbles observed in Pt/Co/Pt trilayers[8] (except that the outer boundaries in [Co/Pt]$_4$ are not as smooth as those in Pt/Co/Pt trilayers), but is quite different from the dendritic patterns in thicker [Co/Pt]$_n$ multilayers.[5–7] In this stage, the reduction in magnetization is due to both the expansion of the existing domains and the nucleation of new domains [Fig. 3(b)]. As H was increased from points 2 to 3, the reversed domains kept growing instead of shrinking until the domain pattern was formed, as shown in Fig. 3(e), at point 3. Between points 3 and 4, although H continued to increase, the reversed regions kept a constant area [represented by Fig. 3(e)], thus the magnetization has a plateau value. Most surprisingly, as H was increased from points 4 to 5 [Figs. 3(f)–3(h)], the reversed dark domains maintain the same outer boundary, while the regions inside became progressively brighter and finally disappeared. This is very unusual behavior, different from that in Pt/Co/Pt trilayers where the outer smooth boundaries retract toward the nucleation centers.[8]

The MOKE imaging results suggest much finer unresolved structures inside the outer boundaries of the reversed domains. Consequently, MFM is used to clarify the situation, imaging the same sample premagnetized to the remnant state

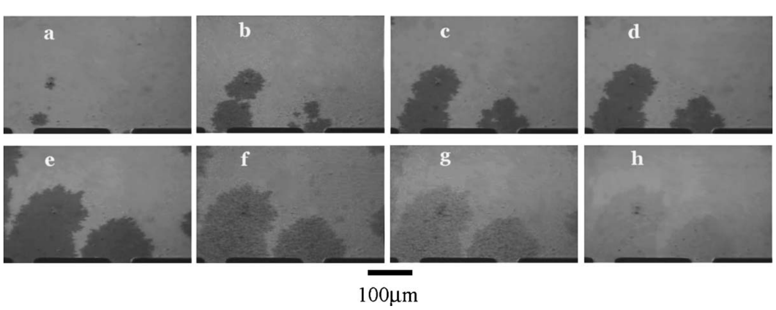

FIG. 3. MOKE images of magnetic domain evolution obtained simultaneously during the FORC measurements, observed at the locations marked by the reference points in Fig. 2; images a–c were taken between points 1 and 2, image d was taken at point 3, image e was taken at point 4, and images f–h were taken between points 4 and 5.

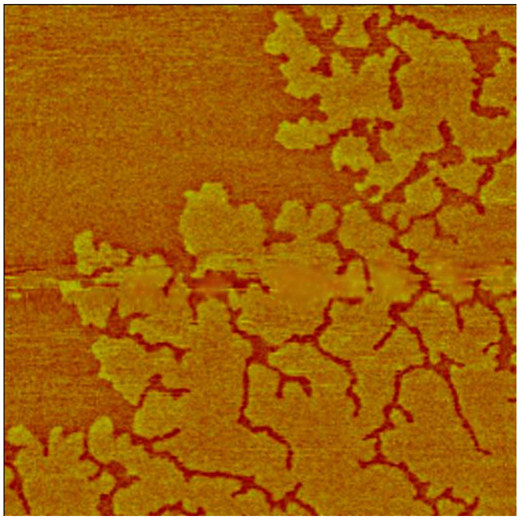

FIG. 4. The MFM image ($50\times 50\ \mu m^2$), obtained at point Q in Fig. 2, clearly shows that there are many submicron-scaled unreversed channels inside the outer boundaries.

shown by point Q, between points 3 and 4 in Fig. 2. Between points 3 and 4 not only does the magnetization remain unchanged but also the MOKE images stay the same. The MFM image (Fig. 4) obtained at point Q clearly shows that there are many submicron-scaled unreversed channels inside the outer boundaries. Therefore, the apparent reversed bubbles are, in fact, not single domains with uniform M inside.

Magnetic domain growth in the thin films with PMA can be realized through two modes: the nucleation of the adjacent new reversed domains and the motion of the existing domain walls.[5,8,10,15] In $[Co/Pt]_n$ multilayers with large n, the nucleation mode dominates, resulting in dendritic domain patterns.[5–7] The domain-wall motion mode dominates in the Pt/Co/Pt trilayers or $[Co/Pt]_n$ multilayers with very small n, resulting in magnetically uniform bubble domains with changing sizes.[8,9]

In contrast, the behavior of the $[Co/Pt]_4$ multilayers with an intermediate n is between the above two limiting cases. When H is decreased from the positive saturation to $-H_T$ (point 2 in Fig. 2), the nucleated domains grow through both the nucleation and domain-wall motion modes, forming the bubble domains with numerous unreversed channels inside the apparent boundaries. When H is increased back from $-H_T$ (between points 2 and 3), the bubble domains first continue expanding by thermally activated domain-wall motions, which overcome the domain-wall pinning. This results in a decrease in M although the external field is increasing. In the plateau region (between points 3 and 4), the external field cannot provide sufficient energy for the domain wall to overcome the wall pinning energy barriers, so the domain-wall motion ceases. Therefore, microscopically the bubble domains remain unaltered, and macroscopically a plateau on the M-H curve is formed. When H is further increased toward the positive saturation field (between points 4 and 5), the domain walls move again, but this time backwards, resulting in the expansion of the previously unreversed channels. Because such domain-wall motions take place only on the submicron scale, the MOKE images on the scale of 100 μm only show contrast changes instead of changes in the outer boundary.

IV. CONCLUSIONS

In conclusion, we have studied macroscopically and microscopically the unusual magnetization reversal behavior of $[Co(4\ \text{Å})/Pt(10\ \text{Å})]_n$ multilayers with an intermediate repeat of $n=4$. We have observed features that are very different from those with either a small or a large n. When measured in an increasing field from $-H_T$ to the positive saturation field, the magnetization exhibits an unusual decrease and plateau. Direct domain observations demonstrate the existence of submicron-scaled unreversed channels inside the apparent much larger macroscopic "bubble" domains. These unusual macroscopic reversal features result microscopically from thermally activated domain-wall motion overcoming domain-wall pinning in $[Co(4\ \text{Å})/Pt(10\ \text{Å})]_4$ multilayers.

ACKNOWLEDGMENT

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