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Journal
JOURNAL OF APPLIED PHYSICS, 109(7)

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Publication Date
2011-03-28

Peer reviewed

JOURNAL OF APPLIED PHYSICS **109**, 07B909 (2011)

Reversal of patterned Co/Pd multilayers with graded magnetic anisotropy

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(Presented 17 December 2010; received 24 September 2010; accepted 22 November 2010; published online 28 March 2011)

Magnetization reversal and the effect of patterning have been investigated in full-film and dot arrays of Co/Pd multilayers, using the first-order reversal curve and scanning electron microscopy with polarization analysis techniques. The effect of patterning is most pronounced in low sputtering pressure films, where the size of contiguous domains is larger than the dot size. Upon patterning, each dot must have its own domain nucleation site and domain propagation is limited within the dot. In graded anisotropy samples, the magnetically soft layer facilitates the magnetization reversal, once the reverse domains have nucleated. © *2011 American Institute of Physics*. [doi:10.1063/1.3554256]

Exchange spring magnet and composite media have received much interest due to important applications in magnetic recording.[1,2] The interlayer exchange coupling lowers the overall coercivity, facilitating the writing process, while the magnetically hard layer provides pinning for the media and ensures its thermal stability. Recently, theoretical work has shown that continuously varying, or grading, the anisotropy between the soft and hard layers can further enhance writability, while preserving thermal stability.[3,4] Experimentally, synthesis of graded anisotropy materials, as well as the ability to characterize the anisotropy gradient have been demonstrated, typically in thin films.[5,6] The full-film geometry is integral to the magnetization reversal process, and often makes it nontrivial to compare with the graded anisotropy models based on isolated grains.[3,4,7] For example, in Co/Pt and Co/Pd multilayers the reversal is dominated by domain nucleation and subsequent propagation laterally along the plane of the film, which convolutes the interpretation of essential parameters such as intrinsic anisotropy and switching field distribution (SFD).[6] It is, therefore, highly desirable to lithographically pattern graded anisotropy materials and investigate the magnetization reversal processes. Such structures are also relevant for bit-patterned magnetic recording media applications.[8]

In this work, we have fabricated Co/Pd multilayer films by varying the sputtering pressure during deposition and then lithographically patterned these films into dot arrays. Increased sputtering pressure has been found to increase the disorder and film roughness, reduce the characteristic domain size, and result in a higher coercivity and a broadened SFD.[9] The behavior of high sputtering pressure films is similar to granular films where reversal is a highly localized process. To the contrary, films sputtered at low-pressures typically undergo reversal by nucleation of a few domains that then propagate by domain wall motion across the full extent of the film.[10]

The samples in this study consist of both full-film and patterned [Co (0.4 nm)/Pd (0.6 nm)]$_{60}$ multilayers grown at room temperature by dc magnetron sputtering.[6] The films were deposited onto the Si substrates with a 20 nm Pd seed layer and capped with 5 nm of Pd. During deposition, the Ar sputtering gas pressure was varied between 0.7 and 2.7 Pa as a function of depth in the film. X-ray diffraction measurements on similar samples[6] show a Pd (111) peak that broadens with increased Ar pressure (roughness), suggesting smaller grain sizes. For films grown entirely at low Ar pressure, a superlattice peak is observed in x-ray reflectometry measurements, indicating good layer quality. The superlattice peak is not discernable in samples grown at higher pressures. A portion of each thin film sample was then patterned into a square array of 1.4 μm circular dots with a 6 μm periodicity using photolithography. Here we focus on four samples.

(1) High pressure: 60 Co/Pd bilayers sputtered entirely at 2.7 Pa.
(2) Low pressure: 60 Co/Pd bilayers sputtered entirely at 0.7 Pa.
(3) Two pressure: Pd seed and first 30 Co/Pd bilayers sputtered at 0.7 Pa, all others sputtered at 2.7 Pa.
(4) Three pressure: Pd seed and first 30 Co/Pd bilayers sputtered at 0.7 Pa, next 15 bilayers sputtered at 1.6 Pa, and all others sputtered at 2.7 Pa.

Magnetic properties were measured using a vibrating sample magnetometer (VSM) at room temperature with the field applied perpendicular to the substrate. Both major hysteresis loop and first-order reversal curves (FORCs) (Refs. 10–12) were measured. FORC measurements are ideal for fingerprinting magnetization reversal processes with the irreversible magnetization quantified by a FORC distribution: $\rho \equiv -\partial^2 M(H,H_R)/2\partial H \partial H_R$, where H_R is the reversal field and H is the applied field along a given FORC. Integrating

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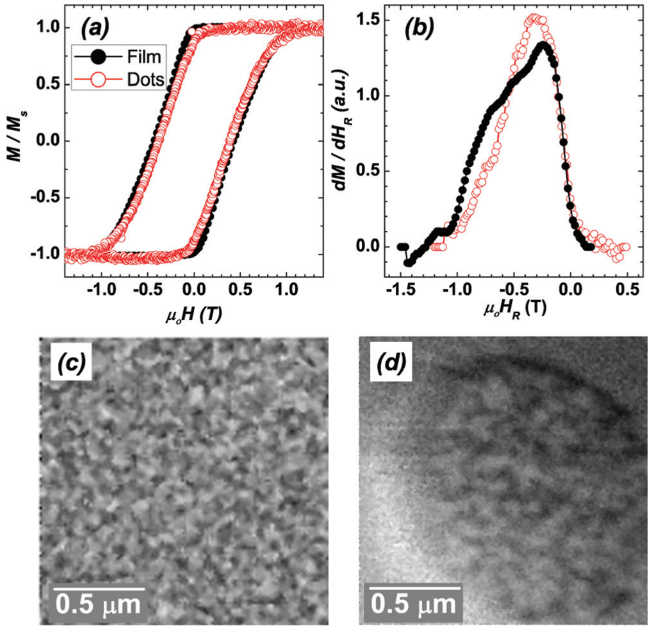

FIG. 1. (Color online) (a) Major hysteresis loops and (b) corresponding FORC-SFD for the full-film (solid symbols) and 1.4 μm dots (open symbols) high-pressure sample, along with SEMPA images of (c) full-film and (d) patterned dots.

ρ over H yields a switching field distribution (FORC-SFD), which can also be used to accurately determine the onset and end point of irreversible switching.[12] Integrating the FORC-SFD over H_R results in the total magnetization that is irreversible (M_{Irrev}).[13] Direct imaging of magnetic domains was performed using scanning electron microscopy with polarization analysis (SEMPA),[14] with the primary focus on the out-of-plane component of the magnetization. Prior to imaging, the samples were dc demagnetized, after saturation in a 1.5 T out-of-plane magnetic field. As SEMPA is a surface sensitive technique, the Pd capping layer was removed *in situ* by Argon backsputtering to expose the top surface of the Co/Pd multilayers.[15]

For the high-pressure sample the major loops for the full-film (solid symbols) and patterned (open symbols) samples are qualitatively similar [Fig. 1(a)]. So do the corresponding FORC-SFDs [Fig. 1(b)]. The amount of irreversible switching is comparable with $M_{\mathrm{Irrev}}/M_S = 0.95$ for the full-film and 0.93 for the patterned sample, where M_S is the saturation magnetization. Thus the reversal process is relatively unchanged in the high-pressure sample with patterning. SEMPA images show a highly textured labyrinth pattern in both samples [Figs. 1(c) and 1(d)] with many small domains ($\sim$0.1 μm width).[16] The small domain size is due to more disorder in the samples as a result of the relatively higher sputtering pressure, which has been previously observed in similar Co/Pt films.[9] Consequently, the size of the contiguous labyrinth domain region is also small, well below the 1.4 μm dot size, and the magnetization reversal is largely unaffected by the patterning.

The full-film low-pressure sample exhibits a distinctly different reversal behavior as compared to the high-pressure sample. Along the descending-field branch of the major loop [Fig. 2(a), filled symbols], there is an initial precipitous drop in magnetization at the nucleation field $\mu_o H_N = 70$ mT, corresponding to the sudden propagation of reversed domains, followed by a more gradual decrease in magnetization approaching the saturation field $\mu_o H_S = -570$ mT. The FORC-SFD shows three distinct regions, a large peak centered at $\mu_o H_R = 10$ mT (corresponding to nucleation and propagation of reversed domains), a flat region (corresponding to expansion/contraction of domains), and finally a second lower amplitude peak around $\mu_o H_R = -450$ mT (corresponding to annihilation of domains). Integrating over the FORC-SFD yields $M_{\mathrm{Irrev}}/M_S = 0.89$. This major loop and FORC-SFD are characteristic of a domain nucleation/propagation reversal process.[10,17] The low-pressure patterned sample's major loop and FORC-SFD [Figs. 2(a) and 2(b), open symbols] are significantly different. Compared to the full-film, the initial magnetization switching is more gradual, and the approach to saturation is faster. The FORC-SFD shows a gradual onset of irreversible switching near $\mu_o H_N = 90$ mT, it then gradually decreases toward saturation at $\mu_o H_s = -570$ mT with *no* second and distinct peak that corresponds to domain annihilation. The total amount of irreversible magnetization is drastically reduced to $M_{\mathrm{Irrev}}/M_S = 0.69$.

The full-film SEMPA image [Fig. 2(c)] shows large areas of interconnected labyrinth domains, whose lateral extent spans several microns, well beyond the size of the patterned dots. As reported in similar Co/Pt films, magnetization reversal from saturation starts from a certain number of nucleation sites, which then grow into labyrinth domains and propagate over the entire sample area; the size of the interconnected domain region is related to the defect density.[18] In the patterned dots, although similar domain topography is observed [Fig. 2(d)], the lateral contiguity of the domains is limited by the edge of the dot. The position of the nucleation peak in the FORC-SFD decreases slightly from 7 mT in the full film to −25 mT in the dots. This shift can be understood

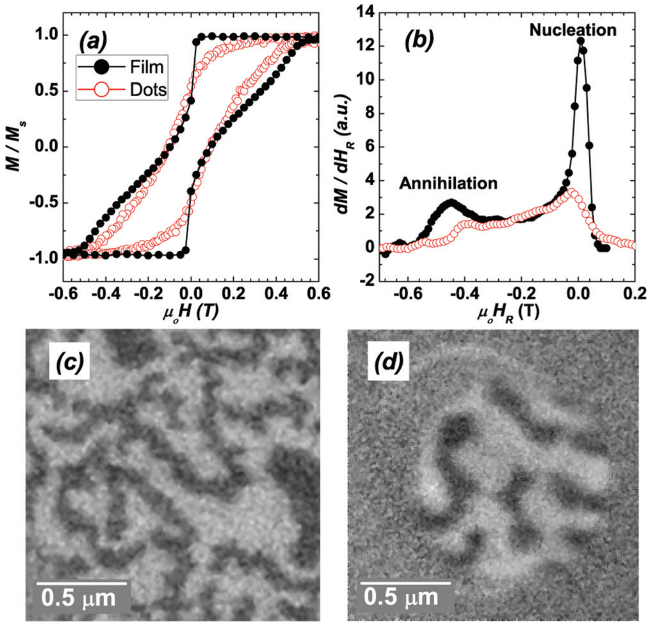

FIG. 2. (Color online) (a) Major hysteresis loops and (b) corresponding FORC-SFD for the full-film (solid symbols) and 1.4 μm dots (open symbols) low-pressure sample, along with SEMPA images of (c) full-film and (d) patterned dots.

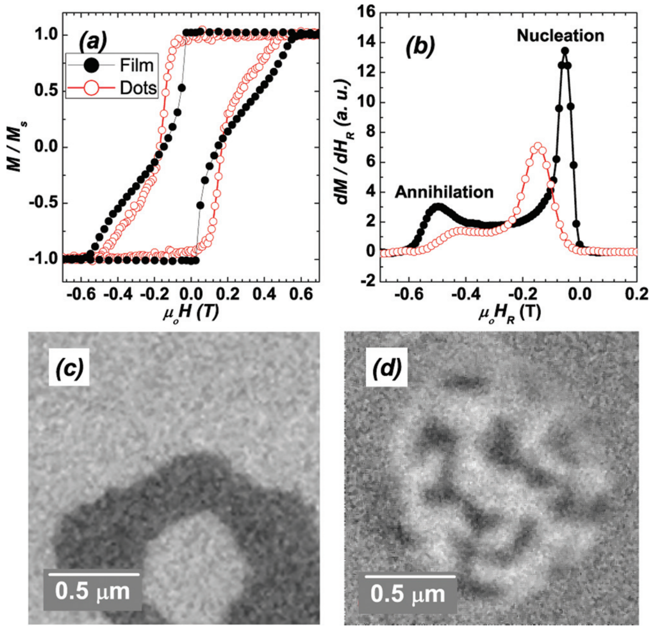

FIG. 3. (Color online) (a) Major hysteresis loops and (b) corresponding FORC-SFD for the full-film (solid symbols) and 1.4 μm dots (open symbols) three-pressure sample, along with SEMPA images of (c) full-film and (d) patterned dots.

by the difference in the domain nucleation events. In the continuous film, magnetization reversal starts at the easiest-to-switch grains; once nucleated, the reverse domains propagate rather easily through the domain wall motion following the least-energy path. The intrinsic switching fields of grains with higher anisotropies are masked in this process. In the patterned dots, each must now have its own domain nucleation site. This leads to a higher average nucleation field with a larger distribution, manifested in the FORC-SFD, and less abrupt magnetization switching in the major loop. Once domains have nucleated, saturation is achieved by domain wall motion to the edge of the dots (largely a reversible process) and is reflected in the lack of a domain annihilation peak in the FORC-SFD and the reduced M_{Irrev}.

For the three-pressure sample the full-film loop [Fig. 3(a), filled symbols] and FORC-SFD [Fig. 3(b)] qualitatively resemble the low-pressure sample, exhibiting three distinct reversal stages with $\mu_o H_N = 0$ T and $\mu_o H_S = -0.60$ T. Patterning [Figs. 3(a) and 3(b)] decreases $\mu_o H_N$ to -0.05 T and increases $\mu_o H_S$ to -0.55 T. The initial nucleation peak in the FORC-SFD and the planar reversible region (second stage of the reversal) are also qualitatively similar to the full-film. However, there is no distinct peak in FORC-SFD that corresponds to domain annihilation. The more pronounced nucleation peak in the patterned dots [Fig. 3(b)], compared to the low-pressure dots [Fig. 2(b)], is likely due to the magnetically harder layers grown at higher sputtering pressures. The added disorder and higher anisotropy result in similar SFD between the full-film and patterned samples, as evidenced in the high-pressure sample having almost identical switching behavior (Fig. 1). Although less pronounced, the nucleation peak in the dots is broader than that in the full-film, and results in a comparable M_{Irrev}/M_S (0.93 and 0.91 for film and dots, respectively). Thus, while there is a reduction in irreversible magnetization switching due to the lack of an annihilation process, the additional nucleation sites are required for reversal to occur in all the dots compensate for this disparity. SEMPA micrographs for these samples [Figs. 3(c) and 3(d)] again show regions of contiguous reverse domains that are much larger than the dot size, similar to the low-pressure case. The large-scale domains imply that once reverse domains have nucleated (which are largely influenced by the magnetically harder layer), it is primarily the magnetically softer low-pressure layers that facilitate the remainder of the reversal process through their exchange coupling to the harder layers.

In conclusion, we have investigated magnetization reversal in graded anisotropy Co/Pd multilayer thin films and patterned dots. The effect of patterning is most pronounced in the low-pressure sample with the least amount of disorder, as the domain nucleation and propagation are limited to the physical size of each dot. In the high-pressure sample with more disorders, the size of contiguous labyrinth domain is smaller than the dot size, and the effect of patterning is negligible. We have also found that layers deposited at high pressure drive the initial nucleation in the two and three-pressure samples.[19] The high-pressure layers tend to make the domain nucleation similar in the full-film and patterned samples, as the added disorders cause a larger distribution of switching fields. Once reverse domains have nucleated, layers deposited at low pressure facilitate the magnetization reversal via domain wall motion through the entire film.

We thank B. J. Kirby and R. D. Shull for fruitful discussions. J.E.D. acknowledges support from NSF (IIP-1013982). Work at UCD was supported by NSF (DMR-1008791 & ECCS-0925626).

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