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Optimization of Co/Pt multilayers for applications of current-driven domain wall propagation

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A series of Co/Pt multilayers with perpendicular magnetic anisotropy has been grown by magnetron sputtering and characterized using magneto-optical Kerr effect measurements with a view to optimizing samples for current-driven domain motion applications. The influence of the thickness of both Co and Pt layers on the coercivity and switching behavior has been systematically investigated. The coercivity was found to depend strongly on the thickness of the Co layer and clear perpendicular magnetic anisotropy was observed in multilayer stacks with Co thickness ranging from 3 to 7 Å. Upon increasing the Co thickness further the magnetization reverts to the in-plane direction and both the coercivity and the remanence drop rapidly, with the former becoming dominated by shape anisotropy. Increasing the thickness of the Pt buffer layer leads to improved perpendicular magnetic anisotropy with higher coercive fields. In contrast, the thickness of the Pt capping layers does not appear to have any systematic influence on the anisotropy in the range of 22–62 Å. The coercivity can be further affected by the number of repeat Co layers in the stack due to exchange and magnetic coupling between adjacent Co layers. Upon increasing the thickness of the intermediate Pt spacer layer beyond 27 Å, a transition from a coherent single-unit-like reversal to a sequential layer-by-layer reversal was observed. Structures with sharp switching fields and medium coercivity (50–150 Oe) have Co thickness fractions in the range 5 ~ 7% of the total stack height and should be well optimized for studying current-driven domain motion at low current densities. © 2011 American Institute of Physics. [doi:10.1063/1.3654045]

I. INTRODUCTION

Co/Pt multilayers with perpendicular magnetic anisotropy (PMA) have been extensively studied for many years with a view to applications in high density magneto-optical media due to their large Kerr rotation angles at short wavelengths.^{1,2} For this purpose, the coercivity of the Co/Pt system is required to be relatively large (~several kOe) in order to stabilize the stored information. More recently, it has become recognized that perpendicular Co/Pt multilayers represent excellent model systems for studying domain wall (DW) physics, in particular current-induced domain wall motion (CIDM).^{3–6} This is, in part, due to the fact that the magnetic anisotropy of Co/Pt multilayers can be systematically modified by ion irradiation.^{7–10} Irradiation allows one to precisely tune the sample anisotropy, controllably increasing domain wall widths and reducing domain wall energies. For such applications a stack with medium coercivity in the range 50–150 Oe and sharp switching fields (indicating rapid and easy domain wall propagation) represent a good compromise between achieving low critical current densities for domain motion while maintaining stability at room temperature.

In a typical Pt/Co/Pt stack containing an ultrathin Co film, a non-magnetic Pt seed or buffer layer is used to induce (111) texture and promote PMA, while a Pt capping layer protects against oxidation. The origins of PMA in the Co/Pt

system have been extensively studied and are known to be linked to strain and alloying at the Co/Pt interface as well as the fact that interface Pt atoms become polarized by Co atoms in their vicinity.^{11,12}

Extraordinary Hall effect (EHE) measurements are frequently used to characterize the magnetization of these ultrathin Co/Pt multilayer stacks with PMA. It is even possible to use this approach to investigate a local regime somewhat smaller than the Hall cross patterned into the transport structure.^{9,13} One challenge of EHE for use with Co/Pt multilayers, however, is that the majority of the applied current flows through the Pt buffer and capping layers and gives rise to little or no Hall voltage. These current “shunt” limitations also apply to the use of magnetoresistive characterization techniques as well as applications of current-induced domain wall motion based on spin transfer torque (STT) when current flow in the Pt layers makes little contribution to the torque but generates significant Joule heating.⁵ Hence, it is crucial that the thicknesses of the non-magnetic Pt layers should be minimized in optimized transport structures, and this is the purpose of the study described here.

In this paper a systematic series of Co/Pt multilayers with different Co and Pt layer thicknesses was grown and their influence on the magnetic anisotropy and coercivity of the stacks investigated. The ultimate aim of this study was to establish the optimum range of layer thicknesses for ongoing investigations of current-driven domain wall motion. Our working assumption is that new domains and DWs will

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initially be nucleated by a prior independent process (e.g., a carefully controlled field cycle or an additional local field pulse), and the experiments we want to perform only relate to DW propagation. Consequently, the magnitude of STT and its influence will depend on the film magnetization to first order, and only indirectly on the anisotropy through the domain wall width. Hence, Co/Pt materials with the minimum density of domain nucleation centers and pinning sites are required to achieve highly mobile domain walls. Low DW pinning materials such as these will be characterized by the sharpness of the switching at the coercive field rather than coercivity itself, which has a domain nucleation component. The main role of the magnetic anisotropy is to control whether STT occurs in the ballistic (high anisotropy, narrow DWs) or adiabatic (low anisotropy, wide DWs) regime and adds an additional experimental control parameter. Hence, we focus on Co/Pt materials with a sharp switching at the coercive field, medium coercivity (a compromise between poor stability at low H_c , and experimental limitations associated with generating rapid high field excursions at high H_c) and tuneable anisotropy. Here, we present the results of this work and discuss the design of samples for future studies.

II. EXPERIMENT

Co/Pt multilayer samples were deposited on (100) Si/SiO₂ substrates at room temperature using dc magnetron sputtering. The base pressure of the sputtering system was 1.4×10^{-7} mTorr and the Ar pressure during the sputtering was 2.5 mTorr. The simplest trilayer structures were composed of a Pt buffer layer, the ferromagnetic Co layer and finally a thin Pt capping layer to protect against oxidation. More complex samples included repeated Co/Pt bilayers to form multilayer samples. Magneto-optical Kerr effect M-H loop measurements were performed in a polar geometry using a 633 nm He-Ne laser. The surface topography of the deposited samples was characterized using an MFP-3 D atomic force microscopy (AFM) from Asylum Research.

III. RESULTS AND DISCUSSION

After deposition, the rms roughness of the completed structure was determined to be in the range of $3 \sim 6$ Å, by AFM measurements. Figure 1(a) shows a $1 \times 1 \mu\text{m}^2$ AFM image from a Pt 47/Co 5/Pt 22 Å film. The roughness of the sandwiched sample was determined to be 5.9 ± 0.2 Å. Figure 1(b) shows that the roughness of sputtered Pt x/Co 5/Pt 22 Å films falls with increasing Pt seed layer thickness. When an 88 Å-thick Pt seed layer was used in the sample, a roughness as low as 2.8 Å was achieved.

Pt 47/Co x/Pt 22 Å multilayer films with Co layer thicknesses varied between 3 and 9 Å were characterized by polar MOKE measurements. Figure 2 shows four typical MOKE loops measured on multilayer samples with the same Pt buffer (47 Å) and capping layer (22 Å) thicknesses but different Co thicknesses. The 3 Å Co sample shows a square loop with perpendicular anisotropy and rather sharp switching behavior. Samples with 5 Å and 7 Å also show good PMA with larger coercive fields, but switching is not quite as sharp. The sample with a Co thickness of 9 Å only shows a

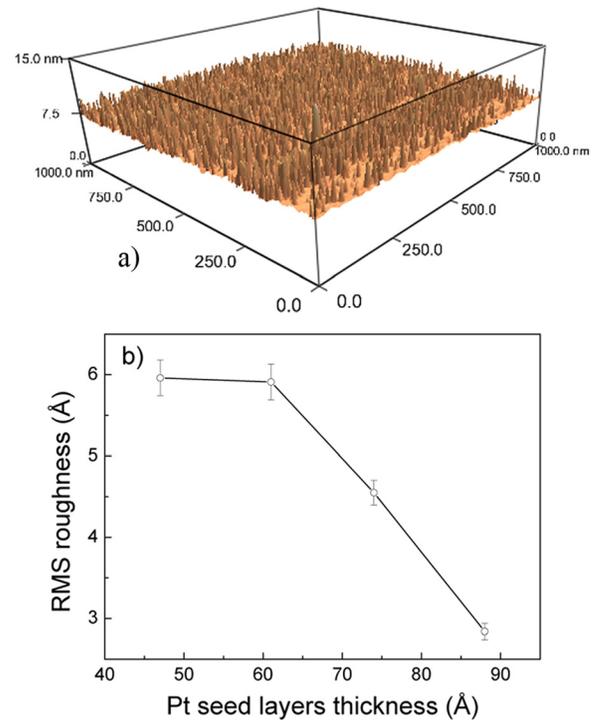


FIG. 1. (Color online) (a) $1 \times 1 \mu\text{m}^2$ atomic force microscopy image of a Pt 47/Co 5/Pt 22 Å film. (b) Plot showing the trend of lower roughness with increasing Pt seed layer thickness for Pt x/Co 5/Pt 22 Å films sputtered on a Si/SiO₂ substrate.

very small remanent ratio of a few percent and extremely rounded hysteresis loops. This suggests that this sample has almost full in-plane anisotropy with shape anisotropy now dominating.¹¹ It has been established¹⁴ that the Pt/Co/Pt trilayer system can be described by an effective first order magnetic anisotropy that includes interface and volume anisotropy terms, which give rise to PMA and a negative shape anisotropy term, which tends to align the magnetization in-plane. The positive contribution from the interface term decreases as the inverse Co film thickness and the easy direction becomes in-plane above a critical Co thicknesses when the effective first order anisotropy changes sign.

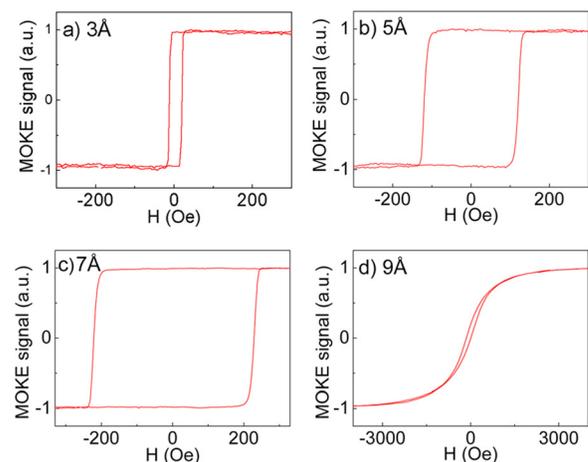


FIG. 2. (Color online) MOKE hysteresis loops for Pt 47/Co x/Pt 22 Å films with Co thicknesses of (a) 3 Å, (b) 5 Å, (c) 7 Å, and (d) 9 Å.

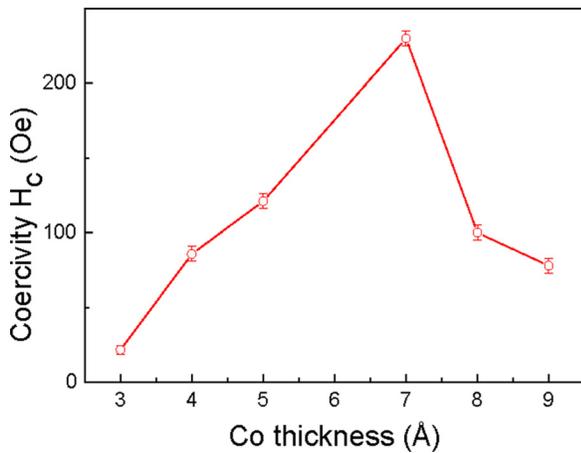


FIG. 3. (Color online) Coercivity of Pt 47/Co x /Pt 22 Å multilayer films as a function of Co layer thickness.

Figure 3 illustrates how the coercivity, H_c , of the films depends on the Co thickness. H_c first increases and reaches a maximum of 230 Oe in the sample with a 7 Å Co layer. As the thickness is increased beyond this point a sharp reduction in coercivity was observed. The very small remanent ratio in these thicker samples indicates that their anisotropy is almost completely in-plane.¹¹ Interestingly, the coercive field appears to show a sharp maximum at a Co thickness of 7 Å just before the magnetization goes in-plane, which was not observed in Ref. 14 where H_c was found to be fairly constant below the reorientation thickness. This observation is not yet fully understood but could be related to the importance of a small second order anisotropy near the spin reorientation thickness, or the influence of stronger DW pinning (switching becomes somewhat broader at larger Co thicknesses).^{14,15}

In a second study the influence of varying the buffer layer thickness was investigated at fixed Co layer (5 Å) and Pt capping layer (22 Å) thicknesses. The resulting MOKE hysteresis loops are illustrated in Fig. 4 and are all very square indicating good PMA. A pronounced increase in coercivity was observed as the Pt buffer layer thickness was increased above 61 Å. Overall we found that the coercivity increased from 120 to 210 Oe as the buffer layer thickness increased from 47 to 88 Å, a change that can be attributed to

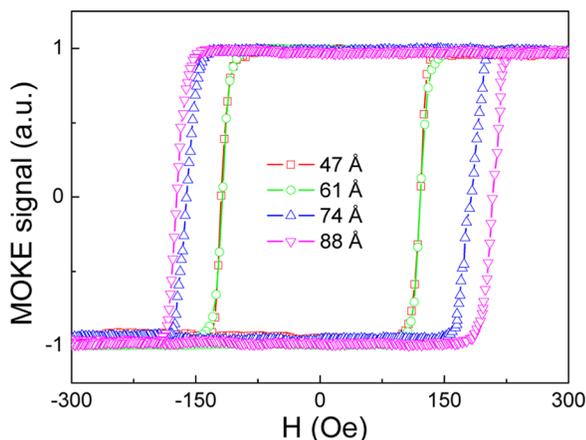


FIG. 4. (Color online) MOKE hysteresis loops for Pt x /Co 5/Pt 22 Å films with different buffer layer thicknesses.

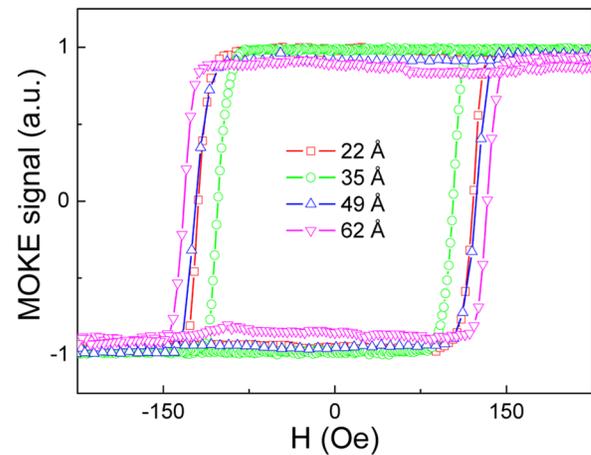


FIG. 5. (Color online) MOKE hysteresis loops for Pt 47/Co 5/Pt x Å films with different capping layer thicknesses.

an improvement in the fcc (111) texturing of the Co layer with thicker buffers.^{11,16–19} In addition, a reduction in Co/Pt interface roughness (c.f., Fig. 1(b)) can enhance interfacial anisotropy, which should also contribute to an increase in coercivity.²⁰

A Pt capping layer was deposited on top of all the samples to protect them against oxidation. Figure 5 illustrates the results of a third study whereby the influence of the cap layer thickness on the magnetic properties was investigated at fixed Co layer (5 Å) and Pt buffer layer (47 Å) thicknesses. We found that the coercivity fluctuated between 103 Oe and 133 Oe as the Pt cap layer thickness increased from 22 to 62 Å, but no systematic (monotonic) trend was observed. It is probable that these differences resulted from random variations of the sample microstructure and interface strain.

In Fig. 6 we show the results of an investigation of the magnetic behavior of multilayer samples containing two Co layers of varying (but equal) thickness separated by a 27 Å Pt spacer. The sample with 3 Å Co layers exhibits a narrow waist in the loop, implying the formation of a multi-domain structure during magnetic reversal.²¹ This incoherent reversal is probably related to the non-uniform coverage of these very thin Co films. Increasing the Co thicknesses to 4 Å and

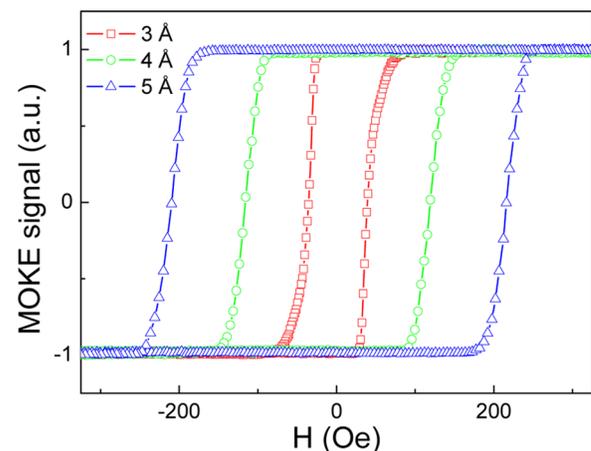


FIG. 6. (Color online) MOKE hysteresis loops for Pt 47/Co x /Pt 27/Co x /Pt 22 Å films containing two Co layers of varying thicknesses.

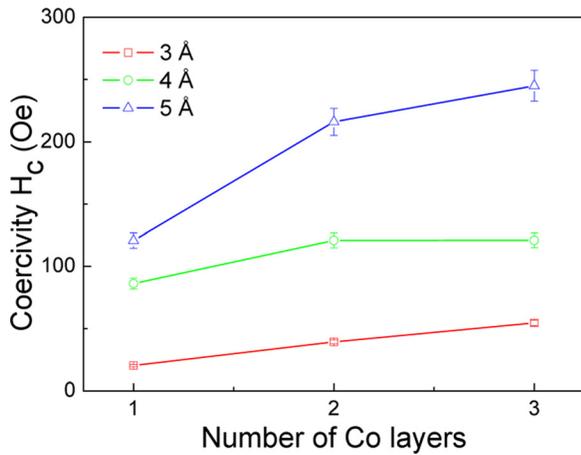


FIG. 7. (Color online) Coercivity of Pt 47/[Co x /Pt 27]_{0.1,2}/Co x /Pt 22 Å films with a different numbers of Co layers.

above resulted in reasonably sharp coherent reversal of both Co layers.

Figure 7 illustrates the coercivity of Co/Pt films with different numbers of Co layers as a function of the (equal) Co layer thicknesses. All the samples had a 47 Å Pt buffer layer, Pt spacer layer thicknesses of 27 Å and a 22 Å Pt capping layer. A clear trend of increasing coercivity is observed as the number of Co layers increases and as the Co layer thick-

nesses increase from 3 to 5 Å. This trend can be attributed to the enhanced magnetostatic interaction between separate Co layers in the stacks as they become thicker.²²

Finally, multilayer stacks of Pt 47/[Co/Pt x]₂/Co/Pt 22 Å with different thickness Pt spacer layers were compared. Figures 8(a) and (b) show MOKE hysteresis loops measured on multilayer stacks with Co thicknesses of 3 Å and 5 Å, respectively. In both cases magnetization reversal is observed to start at lower fields as the thickness of Pt spacer layer increases from 13 to 41 Å. Interestingly, when a 41 Å spacer was used, completely incoherent layer-by-layer reversal is seen in the sample with 5 Å Co layers, while the loop for the equivalent 3 Å sample in Fig. 8(a) shows a pronounced broadening suggesting that something similar is occurring. This multiple switching behavior arises due to the weakened exchange coupling between Co layers with such large spacer layers, as was confirmed by magnetic imaging.²³ The inter-layer exchange coupling decays rapidly as the thickness of the Pt spacer increases leading to decoupling, a trend that may even be enhanced by weak AF alignment at large separations.²⁴ We notice that when a thin Pt spacer layer of 13 Å is used the switching of multilayers becomes slow (i.e., a high field over coercivity is required to complete switching). This slow switching behavior with hard pinning sites arises from the competition between domain wall energy and magnetostatic energy,¹⁵ which will hamper attempts to achieve highly mobile domain walls in STT applications.

IV. CONCLUSIONS

Our results show that the magnetic reversal and anisotropy of Co/Pt multilayers depend strongly on the thickness and number of magnetic Co layers as well as the thickness of non-magnetic Pt buffer and spacer layers. The thickness of the Pt capping layers does not appear to be an important parameter and can be kept as thin as possible while remaining pinhole free in order to prevent oxidation of the Co below. Optimizing the layer design of the whole Co/Pt system is crucial for transport measurements in order to maximize the flow of current through magnetic layers and lower critical current densities for current-driven domain wall propagation experiments. Hence, we wish to reduce the fraction of Pt in the Co/Pt multilayer system in order to minimize current shunting by non-magnetic layers and hence increase the effectiveness of the magnetic component in the stacks. It is known, however, that the interface transmission coefficient between Co and Pt layers also plays an important role in this problem.⁵

To facilitate a comparison, Co/Pt samples with the simplest trilayer structure were chosen to avoid issues associated with complex multi-domain states or incoherent reversal often observed in the multilayers with many repeats. Figure 9 shows a plot of the coercivity of trilayer samples as a function of Pt seed layer and Co layer thicknesses, which are of primary importance in determining the magnetic properties of our materials. In the figure, the red dots show the composition of samples possessing sharp switching fields and medium coercivity (~ 50 – 150 Oe). The region of phase space highlighted by the dashed circle encloses Pt/Co/Pt trilayer structures with sharp switching fields and medium coercivity

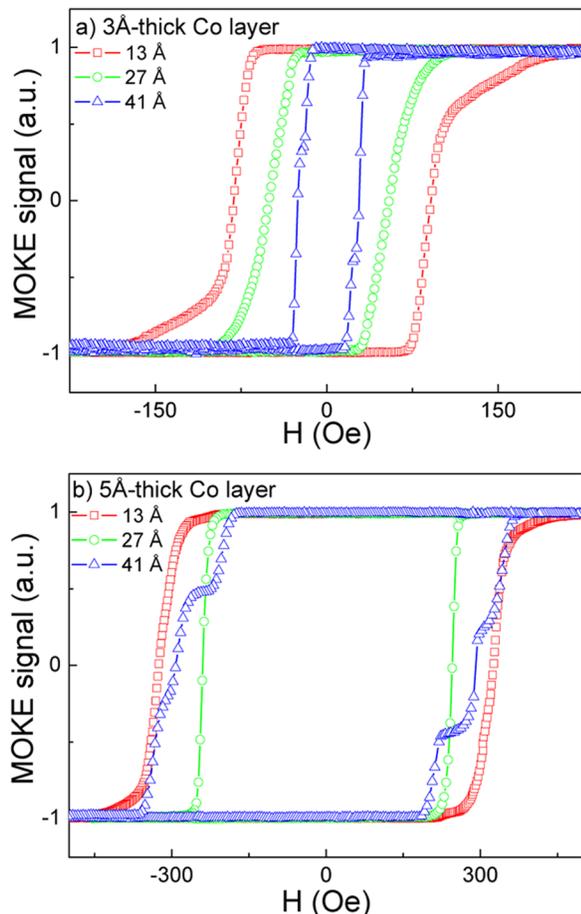


FIG. 8. (Color online) MOKE hysteresis loops for Pt 47/[Co/Pt x]₂/Co/Pt 22 Å multilayers with different thickness Pt spacer layers. The Co thicknesses are (a) 3 Å and (b) 5 Å, respectively.

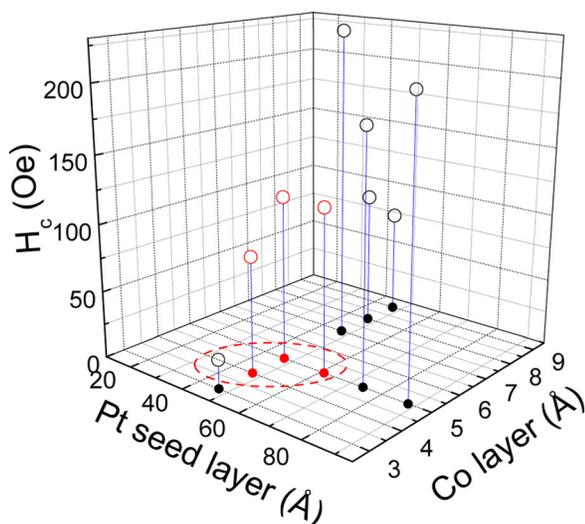


FIG. 9. (Color online) A plot of coercivity of trilayer samples as a function of Pt seed layer and Co layer thicknesses. The capping layer thickness does not significantly influence the magnetic properties (c.f., Fig. 5). The red dashed circle highlights compositions suitable for current-driven domain wall propagation applications.

that have Co thickness fractions in the range 5 ~ 7% of the total stack height and should be well optimized for studying current-driven domain motion at low current densities.

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