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Study of structure, magnetism and transport properties of magnetic thin films

Abstract

This report presents part of the results of the J.C.A. Huang under the support of NSC 89-2112-M-006-037. We focus here on the study of perpendicular magnetic anisotropy of CrPt$_3$ films. The publication of the J.C.A. Huang in the recent three years can be found in appendix. Perpendicular magnetization and Kerr effects of epitaxial CrPt$_3$ films have been studied as functions of the crystal orientation, alloy composition and growth temperature. We have designed careful experiments to control single growth parameter at each run. The orientation dependence studies reveal that only the (111) oriented CrPt$_3$ films possess perpendicular magnetization, while the (311) and (100) films are in-plane magnetized. The composition and temperature dependences show that the CrPt$_3$ films possess optimal perpendicular magnetization and Kerr effect at x=3 and growth temperature 850°C. The optimal composition and temperature conditions are accompanied with the best L2$_3$ ordering parameter, indicating that the perfection of L1$_{2}$ (111) structure is crucial for the perpendicular magnetization in this system. We demonstrate here a systematic approach to rapidly obtain optimal growth conditions for binary alloys such as CrPt$_3$ films.

Keywords: Perpendicular magnetization, Kerr effect, Molecular beam epitaxy (MBE) growth, optimal growth condition.

Introduction

Magnetic thin films with large perpendicular magnetic anisotropy (PMA) have recently received much attention for basic research and applications. For example, chemically (CuAu, Li$_3$) ordered MPt(001) (M=Fe, Co) films show strong PMA effect and polar Kerr rotations and are promising materials for high-density magnetic and magneto-optical (MO) recording. In ordered MPt(001) alloy films, the reduced thickness of the M layer to a single monolayer together with symmetry breaking in the M-Pt (001) interface result in the perpendicular magnetization alignment. MPt$_3$ (M=Mn, Co, Fe, Cr) alloy films have also attracted considerable interest owing to their rich magnetic structure and possible application for recording. Ordered MPt$_3$ films all crystallize in the cubic Cu$_3$Au (L1$_2$) structure. However, they display distinct magnetic orderings (ferromagnetic, anti-ferromagnetic or ferromagnetic) and alignments (in-plane or out-of-plane). Ordered MnPt$_3$ films display large Kerr effect but with in-plane magnetization. Fully ordered CoPt$_3$ films also show in-plane ferromagnetism, whereas partially ordered CoPt$_3$ films exhibit good PMA effect. Further, an ordered, stoichiometric FePt$_3$ compounds may show anti-ferromagnetic ordering. In contrast, ordered CrPt$_3$ compounds are ferrimagnets with the magnetic moment of Cr and Pt aligned anti-parallel to each other.

For binary alloys systems such as MPt and MPt$_3$, PMA and Kerr effect is sensitive to the crystal orientation, alloy composition, and chemical ordering of the alloy films. To understand the origin of perpendicular magnetization in these binary alloy systems, it is thus important to carry out systematic studies on the critical growth parameters – crystal orientation, composition, and growth temperature. However, it is generally difficult to study a single growth parameter with the other ones fixed. For temperature dependence study, for instance, it is hard to have precise control of the alloy composition. Therefore, usually it takes much effort to have complete studies on these critical growth parameters.

In this paper, we study the perpendicular magnetization of CrPt$_3$ films as functions of the crystal orientation (O), alloy composition (X) and growth temperature (T). By special sample growth technique (discussed below), we demonstrate here a systematic approach to rapidly obtain optimal growth conditions for binary alloy such CrPt$_3$ films. We have designed and carried out careful experiments to control only single growth parameter at each run. First, by simultaneous growth of CrPt$_3$ films on distinct substrates (with X and T fixed), the crystal orientation of the epitaxial films can be selected. Secondly, the thickness wedge samples allow us to study the PMA effect as a function of alloy composition (with O and T fixed). In addition, we have designed a temperature wedge sample holder so the growth temperature of the epitaxial films can be varied almost linearly from one end to other (with O and X fixed) on one substrate. Optimal growth parameters for perpendicular magnetization of CrPt$_3$ alloy films were thus determined. To rapidly and effectively obtain the optimal growth parameters, we believe this kind of approach can be applied to a binary alloy systems or even more complicated cases.

Sample preparation and characterizations

The CrPt$_3$ films were grown by a Vacuum Product
made molecular beam epitaxy (MBE) system. Details of the chamber in which crystal growth took place were provided elsewhere.\textsuperscript{15,16} To enable the growth of high-quality samples, the sapphire and MgO substrates were outgassed at 1000°C for 1h before the initial deposition. Pure (99.99%) Cr and Pt elements were evaporated from a separate e-beam source. The CrPt$_3$ films were prepared by trilayer growth of Cr(55 Å)/Pt(100 Å) (or 50 Å)/Cr(55 Å) thickness wedge at 850°C (Fig. 1(a)). For temperature wedge studies, the CrPt$_3$ films were prepared by multilayer growth (20 repeats of Cr(10 Å)/Pt(20 Å)/Pt(35 Å) bilayers) at temperatures from about 600°C to 950°C. For temperature dependence studies, the CrPt$_3$ films were prepared by multilayer growth at 850°C. The multilayer growth provides accurate thickness control of Cr and Pt layer (thus alloy composition) and high growth temperature can promote good alloying effect between the Cr and Pt layers.

The deposition rates of the Cr or Pt layer were controlled at \( \approx 0.1\ \text{Å/sec} \) with the growth pressures below \( 5 \times 10^{-9} \) torr. To select the crystal orientation, CrPt$_3$ films were simultaneously grown on epitaxial grade Al$_2$O$_3$(0001), Al$_2$O$_3$(11-20), Al$_2$O$_3$(1-100), MgO(001) substrates. By using trilayer growth (Cr/Pt/Cr) at high temperature and simple mask technique during the growth of Pt layer, for example, the CrPt$_3$ thickness wedge films can be grown with desired range (selecting by the range of Pt thickness for fixed Cr layer thickness) of alloy composition on one substrate, as schematically illustrated in Fig. 1(a). Further, the temperature-wedge sample holder design (Fig. 1(b)) allows the growth temperature being almost linearly changed from high-temperature side (contact side) of the substrate to other end. The adjustment of holding screws in the contact side can tune the substrate tilt angle \( \theta \) (Fig.1(b)) from the sample holder which in turn enable the control of the temperature gradient in the sample. For 6-7\(^\circ\), for example, the temperature gradient was of about 50°C/cm for the sapphire substrates in our system. The substrate temperatures can be calibrated by two of thermal couples at both ends of the substrate.

The crystal structure and epitaxial relations was studied by reflection high-energy electron diffraction (RHEED) and x-ray diffraction (XRD). MO and magnetic properties were investigated by polar magneto-optical Kerr effect (PMOKE) using He-Ne laser (\( \lambda \sim 632.8\text{nm} \)).

Results and Discussions

By MBE growth, (111), (311), (001) oriented CrPt$_3$ films were grown on various substrates. CrPt$_3$(111) were prepared on Al$_2$O$_3$(0001) and Al$_2$O$_3$(11-20) substrates, while CrPt$_3$(311) and CrPt$_3$(001) films were stabilized on Al$_2$O$_3$(1-100) and MgO(001) substrates, respectively. Note that the CrPt$_3$(111) films were grown as single-crystal on Al$_2$O$_3$(0001) substrate, but with ninety-degree domains on Al$_2$O$_3$(11-20) substrate, as evidenced by RHEED and in-plane XRD studies study. Details of the surface and bulk quality of these CrPt$_3$ films and three-dimensional epitaxial relations will be reported elsewhere.\textsuperscript{18} In this paper we focus on the perpendicular magnetization and Kerr effects as functions of the crystal structure, alloy composition and growth temperature in CrPt$_3$ films.

Figure 2 shows the PMOKE hysteresis loops of the CrPt$_3$ (alloy composition within 3% of accuracy) films simultaneously grown on four distinct substrates at an optimal temperature of about 850°C (determined by temperature wedge). Clearly, (111) oriented CrPt$_3$ films possess perpendicular magnetization while the (311) and (001) oriented films were in-plane magnetized. In addition, the PMA effect of the single-crystal CrPt$_3$(111) (on Al$_2$O$_3$(0001)) is much better than the textured CrPt$_3$(111) (on Al$_2$O$_3$(11-20)) with two in-plane domains. The latter case is due to the mismatch of crystal symmetry between fcc CrPt$_3$(111) (six fold) and Al$_2$O$_3$(11-20) plane (two-fold, nearly four-fold). Therefore, for the following studies of thickness wedge and temperature wedge, we employ Al$_2$O$_3$(0001) as the underlying template for CrPt$_3$ films.

Figures 3(a) shows the PMOKE hysteresis loops of the (111) oriented CrPt$_3$ (1.75\%<\%<4.25) thickness wedge samples grown on Al$_2$O$_3$(0001) substrate at 850°C. The optimal polar Kerr effect and loop squareness occur at x~3, as shown in Fig. 3(b)-(c). This together with the order parameter measurements\textsuperscript{18} indicates that the perfection of L1$_2$(111) structure is important for the perpendicular magnetization and Kerr rotation in this system. Note that the alloy compositions of the CrPt$_3$ films were determined by a linear fitting\textsuperscript{19} of the lattice parameters obtained from the 6-20 XRD scans, as shown in Fig. 4. In addition, the order parameters of CrPt$_3$ (111) films can be decided by measuring the intensity ratio of the tilted (112) and (113) peaks as reported by Maret in ref. [17].

Figure 5(a) shows the PMOKE hysteresis loops of the temperature wedge (605°C<\%<955°C) CrPt$_3$(111) samples grown on Al$_2$O$_3$(0001) substrate. The optimal polar Kerr effect and loop squareness occur at T~870°C, as shown in Fig. 5(b)-(c). Note that the synchrotron XRD measurements\textsuperscript{18} show that the order parameters of the L1$_2$(111) structure also have a peak position at growth temperature around 850°C, supporting that the perfection of L1$_2$(111) structure is crucial for the PMA effect and Kerr rotation for CrPt$_3$ films. It is also noted that the optimal growth of CrPt$_3$ films is much lower than the order-disorder transition (\approx 1100°C) of bulk CrPt$_3$ compound, indicating the importance of surface kinetics (e.g. surface disordering) during MBE thin film growth processes.

In conclusion, we have successfully grown high-quality CrPt$_3$ films by MBE technique and studied the perpendicular magnetization as functions of the crystal orientation, alloy composition and growth temperature. We have designed and carried out careful experiments to control only single growth parameter at each run. The orientation dependence shows that only the (111) oriented CrPt$_3$ films possess perpendicular magnetization. The composition and temperature dependences show that the CrPt$_3$ (111) films possess optimal perpendicular magnetization effect at X~3 and T~850°C, and both conditions giving the best chemical ordering parameter. The results indicate that the perfection of L1$_2$(111) structure is important for the PMA effect and Kerr rotation for CrPt$_3$ films.
Reference

Fig. 1 Schematic diagrams showing (a) the CrPt\textsubscript{x} thickness wedge grown by Cr/Pt/Cr trilayer (at high temperature of 850°C) and (b) the temperature-wedge sample holder.

(a)

![Schematic Diagrams](image)

(b)

![Substrate Orientation](image)

Fig. 2 POMOKE hysteresis loops scanned from 500 Å thick CrPt\textsubscript{x} films simultaneously grown on Al\textsubscript{2}O\textsubscript{3}(0001), Al\textsubscript{2}O\textsubscript{3}(11-20), Al\textsubscript{2}O\textsubscript{3}(1-100), and MgO (100) substrates at 850°C.

Fig. 3 (a) POMOKE hysteresis loops scanned from CrPt\textsubscript{x}(111) thickness wedge samples grown on Al\textsubscript{2}O\textsubscript{3}(0001) substrate at 850°C, and (b) and (c) the corresponding Kerr rotation and loop squareness as a function of alloy composition x.
Fig. 4 Lattice parameters of the CrPt₃(111) films determined by 0–2θ XRD scans (squares) by this work and by Waterstrat (circles, see ref. [19]). A linear fit of these data gives us the chromium composition.

Fig. 5 (a) PMOKE hysteresis loops scanned from CrPt₃(111) temperature wedge samples grown on Al₂O₃(0001) substrate, and (b) and (c) the corresponding Kerr rotation and loop squareness as a function of growth temperature $T_g$.

Appendix – Publication of J.C.A. Huang in the recent three years


35. J.C.A. Huang, L.C. Wu, J.C. Wu, T.H. Wu, and C.H. Lee,


國立成功大學國科會專題計畫下出席國際會議報告

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報告內容應包括下列各項：
一、參加會議經過
二、與會心得
三、考察參觀活動（無事項活動者省略）
四、建議
五、攜回資料名稱及內容
六、其他
2001年 M&M-Intermag 國際磁學聯合大會會議報告

一、参加会议经过

2001年國際磁學聯合大會於1/9-1/11於美國德州聖安東尼市(San Antonio)舉行。本會議是由兩年舉辦一次，將比較重視基礎研究的 M&M 會議及重工業應用的 Intermaq 會議合辦在一起。本會議之論文摘要須在三個月以前經由網路註冊線上繳交，並經過嚴格審核後才有機會被接受。由於投稿的論文摘要甚多(超過 3300 篇)，其拒絕率約有 40% - 50%，競爭之激烈可見一般。

二、感想心得

本次會議有幾個課題特別受到重視。例如 FePt, CoPt 合金及多層膜具有垂直磁化效應的系統有超過 100 篇的論文發表，原因是水平磁記憶已接近其最高密度極限，而發展垂直磁記憶的課題日益重要。

另外，交叉磁極耦合（Antiferromagnetic coupled）而成之磁性記憶體也備受注目。主要的原因它有較高之磁矩乘以厚度 (M.t) 性質，可改善磁記憶之靈敏度與穩定性。

此外，奈米級 (nano-scale) 磁性材料——如 Nano-dots, Nano-wires, nano-particles 等在基礎研究(如尺寸引起的奇特物性)及工業應用
這具重大價值之系統亦受到相當重視。

三、建議

從軟件台灣出席國際磁性材料會議的現狀及分析，國內在磁學和磁性材料的研究水準日益提高，惟我國之研究人力尚未達到一顛峰高度，又較缺乏團隊合作研究的方式，故整體而言落後於美日等先進國家仍有一段距離。

由於磁性薄膜材料在電脳（硬碟記錄、讀寫頭）、通訊（RF、microwave）皆具有重大實際應用潛力，故筆者建議更加重視磁性薄膜之發展，或者可以類似奈米材料的方式，特別提案研究經費，主動邀集整合研究計劃，甚至規劃出重要研究主題。由於我國的磁學產業及研究已屬世界大國，磁性材料在磁性工業可說是幾乎所有（如可錄式、從事硬碟片生產），值得產業界各階層之重視。

四、儲面資料名稱及內容

"Abstract book of the 2001 MMM-Intermag Joint Conference"
Structure and magnetism in Co/Pt multilayers

J. C. A. Huang
Physics Department, National Cheng-Kung University, Tainan, 70101, Taiwan

C. H. Lee and K. L. Yu
Department of Engineering and System Science, National Tsing-Hua University, Hsinchu, 30043, Taiwan

The structure of \([Co(t_{Co})/Pt(10 Å)]_{30}\) multilayers has been studied by x-ray absorption spectroscopy and x-ray diffraction using in-plane and out-of-plane polarized synchrotron radiation. The x-ray absorption near-edge spectroscopy shows that the Co layer is like a fcc pseudomorphic structure for \(t_{Co} \leq 4 Å\). For \(t_{Co} = 10 Å\), the spectra in both directions are separated and look closer to the bulk hcp Co. The extended x-ray absorption fine structure studies reveal that the Co–Pt interface of the multilayers fitted with a sharp boundary better than an interdiffusion model. The in-plane x-ray diffraction shows that the Pt layer in the multilayer possesses a 2%–3.5% compressible strain. Although the saturation magnetization \(M_s\) does not depend on \(t_{Co}\) or interfacial roughness in any simple form, the \(M_s\) values scale quite linearly with the in-plane Pt strain. We conclude that the interfacial strain is important for the perpendicular magnetization in the Co/Pt multilayers. © 2001 American Institute of Physics. [DOI: 10.1063/1.1354580]

The structure and magnetism of magnetic multilayers (MLs) composed of modulated ferromagnetic-nonferromagnetic (PFN) layers have attracted much attention in recent years. For instance, Co/Pt MLs with large perpendicular magnetic anisotropy (PMA) and Kerr rotations have received considerable interest for basic research and application for high density data storage. The PMA effect can exist in the magnetic multilayer as a consequence of symmetry breaking at the FNF interface. Therefore understanding of the interfacial structure is crucial for the PMA effect. Co/Pt films have been studied by the MCD effect, where a fcc pseudomorphic layer and PMA effect was found for Co less than 5 monolayers. Previously we also reported the epitaxial growth and the magnetic and magnetooptical properties of the Co/Pt MLs. We found that the magnetization of the Co/Pt MLs was perpendicular to the film surface for a Co layer thickness \((t_{Co})\) less than about 6 Å. In addition, it has also been predicted that the PMA for the multilayer might be strain and interfacial roughness related. We were thus motivated to probe the structure difference of Co/Pt MLs with distinct ultrathin Co layer thickness. (111) oriented \([Co(t_{Co})/Pt(10 Å)]_{30}\) (\(t_{Co} = 1.6–10 Å\)) MLs studied here were synthesized by the molecular beam epitaxy (MBE) technique. The details of the MBE system and sample preparation procedures have been described elsewhere.

To probe the local structure of the ultrathin Co layer, both the in-plane and out-of-plane x-ray absorption spectroscopy were performed in a Wiggler beamline of Taiwan Light Source (TLS). The absorption spectra were performed using the fluorescence mode with sample surfaces rotated at an angle either parallel to or nearly perpendicular to the polarization of the synchrotron light. For the reference spectra of hcp-Co foil, and CoPt and CoPt alloys were also taken. The energy resolution is about 1 eV in the x-ray absorption near edge spectroscopy (XANES) region and 3 eV in the extended x-ray absorption fine structure (EXAFS) region. The crystal orientation, strain, and interfacial roughness of the Co/Pt MLs were also measured using x-ray diffraction (XRD) and x-ray reflectivity. The magnetization values and hysteresis loops of the Co/Pt MLs were measured by a vibrating sample magnetometer (VSM).

Figure 1 shows the derivative spectra of Co K-edge XANES for the Co/Pt MLs and the referencing samples. Note that the XANES spectra in the in-plane and out-of-plane directions are quite similar for samples with \(t_{Co}\) less than 4 Å. This result suggests that the Co layer is more like a fcc pseudomorphic structure at a thickness of less than 4 Å because the symmetries along the in-plane and out-of-plane directions are much the same. For \(t_{Co}\) increased to 10 Å, in contrast, the XANES spectra in both directions are separated and look very similar to the bulk hcp Co. It is possible that a fcc to hcp structural transition occurs at \(t_{Co}\) of about 3 to 4 Å. Note that the x-ray absorption spectroscopy data of the Co/Pt multilayer with Co layer thickness of about 1 monolayer is quite similar to the ordered CoPt alloy. Both cases reveal good PMA effect.

Table 1 summarizes the EXAFS fitting parameters including the calculated neighboring distance, coordination number of surrounding Pt atoms, and the Debye–Wall factor. These parameters are obtained by the fitting procedure where the number of Co neighbors has been fixed (to 12). For a \(t_{Co}\) layer of 10 Å, the bonding distance of the first shell is 2.5 Å, which is very close to the Co–Co distance in the bulk hcp Co. On the other hand, for a Co layer of less than 3 Å, the in-plane first shell distance of Co is expanded by about 3% to 4%. To understand the interfacial morphology in the Co/Pt MLs, we compare the EXAFS results with two models, a sharp boundary model and a total interdiffusion model. Figure 2 plots the EXAFS fitting parameter of Pt coordination numbers around the Co atom for the Co/Pt MLs and alloys as well as those predicted by the two models. It appears that both in-plane and perpendicular data from the
the interdiffusion model. Note that the interfacial roughness determined from the x-ray reflectivity is about 3–5 Å for all the Co/Pt MLs. The relatively large interfacial roughness deduced from the x-ray reflectivity does not contradict the sharp boundary model because distinct length scales are probed between the x-ray reflectivity and the EXAFS measurements. The x-ray reflectivity takes a lateral average over a length scale of several microns, but the EXAFS probes only local environment on the angstrom scale. So the sharp boundary indicates that the Co/Pt interface is a jagged one instead of an interdiffused one. The result suggests that significant interdiffusion in the Co/Pt interface did not occur even at a growth temperature of 200 °C. This is in good agreement with the recent Auger experiments, where the interdiffusion of Co on Pt was found to be significant only at temperatures higher than about 280 °C.

The nearest atom distances follow the same trend for both in-plane and out-of-plane directions. This implies that the Co/Pt multilayers might not be Poisson materials in

Co/Pt MLs fits the sharp boundary model much better than

The EXAFS fitting parameters for the out-of-plane (upper) and in-plane (bottom) polarization for Co/Pt multilayers and alloys. Here R is the first shell bonding distance, \( \sigma^2 \) is the Debye–Waller factor, and \( n_h \) is the Pt coordination numbers around the Co atom.

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<td>Co(<em>{25})Pt(</em>{10})</td>
<td>2.53 ± 0.025</td>
<td>7.5 ± 2</td>
<td>2.3 ± 2</td>
</tr>
<tr>
<td>Co(<em>{25})Pt(</em>{10})</td>
<td>2.62 ± 0.026</td>
<td>9.1 ± 2</td>
<td>7.0 ± 2</td>
</tr>
</tbody>
</table>

FIG. 2. The Pt coordination numbers around the Co atom for the Co/Pt MLs and alloys obtained from experiments (circle and square, respectively) and EXAFS fitting. The prediction from sharp boundary and interdiffusion models (triangle) are also plotted for comparison.
TABLE II. The determined structural parameters (by x-ray diffraction and reflectivity) together with the magnetic properties (by VSM) as functions of Co thickness for the Co/Pt multilayers.

<table>
<thead>
<tr>
<th>Cobalt thickness (Å)</th>
<th>Interface roughness (Å)</th>
<th>In-plane strain of Pt(2-20) (%)</th>
<th>Rocking curve width of Pt(2-20) (deg)</th>
<th>$M_s$ (emu/cc)</th>
<th>$H_c$ (kOe)</th>
<th>Squareness of hysteresis loops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>3.0</td>
<td>-2.64</td>
<td>10.5</td>
<td>317</td>
<td>4.1</td>
<td>0.963</td>
</tr>
<tr>
<td>1.8</td>
<td>3.5</td>
<td>-2.34</td>
<td>3.1</td>
<td>281</td>
<td>4.8</td>
<td>0.998</td>
</tr>
<tr>
<td>1.9</td>
<td>3.0</td>
<td>-2.47</td>
<td>4.8</td>
<td>187</td>
<td>5.1</td>
<td>0.976</td>
</tr>
<tr>
<td>4.0</td>
<td>4.5</td>
<td>-3.52</td>
<td>4.6</td>
<td>755</td>
<td>1.6</td>
<td>0.969</td>
</tr>
<tr>
<td>4.3</td>
<td>4.5</td>
<td>-2.73</td>
<td>2.3</td>
<td>426</td>
<td>1.3</td>
<td>0.949</td>
</tr>
<tr>
<td>10.7</td>
<td>3.0</td>
<td>-2.51</td>
<td>3.1</td>
<td>689</td>
<td>0.4</td>
<td>0.107</td>
</tr>
</tbody>
</table>

which the typical Poisson ratio for the bulk material is applicable. The Debye-Waller factors fitted from the EXAFS data taken are also shown in Table I. The results indicate that the Debye-Waller factors obtained from the out-of-plane is larger than that from in-plane direction (and larger than that of CoPt alloys), even though the nearest neighbor distances along the plane normal are slightly larger than that along the in-plane direction. This might suggest that the crystal growth along the plane normal consists of more defects or stacking faults than the in-plane direction. However, in contrast to the in-plane strain of the Pt layer, the Co near shell distance is not correlated with the in-plane strain of Pt (see Tables I and II). Indeed, a maximum strain occurs at a structural phase transition thickness for Co layer thickness of about 4 Å.

The XRD results indicate that the Pt layer in the multilayer possesses a compressible strain of about 2%–3.5% along the Pt[1-10] direction. Samples with large in-plane mosaic (about 2°–10°) and small coherence length (about 20–28 Å) were measured, indicating a plastic deformation of the Pt layer resulting from the lattice misfit (10%) between the Co and Pt layer. The structural parameters obtained from the x-ray diffraction and x-ray reflectivity for the Co/Pt MLs are summarized in Table II. Table II also lists the (VSM measured) magnetic parameters, the saturation magnetization $M_s$, polar coercivity $H_c$, and loop squareness. Note that the change of $H_c$ and squareness reveals a transition of the PMA effect at a Co thickness of about 4 to 5 Å. Interestingly enough, although the saturation magnetization $M_s$ does not depend on $t_{Co}$ or interfacial roughness in any simple form, the $M_s$ values scale quite linearly with the in-plane Pt strain (except for the non-PMA sample with $t_{Co} = 10$ Å), as illustrated in Fig. 3. This result leads to a speculation that a larger strain of the Pt layer might imply a less strained Co layer, which in turn might give rise to a higher value toward the bulk Co value (1420 emu/cc). On the other hand, the polar coercivity does not scale in any simple relation with the Pt strain or any other structural parameters, indicating that the coercivity is more likely a magnetic domain related parameter. We conclude that the interfacial strain is important for the perpendicular magnetization in the Co/Pt multilayers.

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