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On the Physics of Magnetic Anisotropy in Co/Pd Multilayer Thin Films

Darren Smith[1], Shishan Zhang[2], Wolfgang Donner[3], Chunsheng E[1], T Randall Lee[4], Sahkrat Khizroev[5], and Dmitri Litvinov[1]
[1]Electrical and Computer Engineering, University of Houston, Houston, TX, 77004
[2]Chemical and Biomolecular Engineering, University of Houston, Houston, TX, 77004
[3]Physics, University of Houston, Houston, TX, 77004
[4]Chemistry, University of Houston, Houston, TX, 77004
[5]Electrical Engineering, University of California - Riverside, Riverside, CA, 92521

ABSTRACT

$(Co/Pd)_N$ multilayers with Co and Pd layer thicknesses of only a few monolayers exhibit high vertical magnetic anisotropy and have been extensively explored as recording medium candidates for high density magnetic recording applications. In the work reported here, the magnetic properties of $(Co/Pd)_N$ multilayers deposited by magnetron sputtering and designed for bit-patterned medium applications are correlated with X-Ray Photoelectron Spectroscopy (XPS) data -- an approach commonly used to probe the binding energies and valence band positions. Although the XPS probing depth is limited to ~2-3 nm, it is sufficient for the evaluation of the 1-2 topmost bilayers in a multilayer stack, and allows us to infer the relevant details of the bandstructure of the entire film. Confirming theoretical predictions, we demonstrate that the degree of d-shell hybridization at Co/Pd interfaces directly correlates with the magnitude of the magnetic anisotropy. Significantly, the highest hybridization of Pd atoms is observed for about one monolayer thick Co layers in the bilayer stack. Variation of the deposition conditions (e.g., deposition pressure) shows a measurable influence on d-electron hybridization, multilayer microstructure, and magnetic anisotropy.

INTRODUCTION

$(Co/Pd)_N$ multilayer films in which the cobalt and palladium layers are only a few monolayers thick exhibit high magnetic anisotropy perpendicular to the film surface, where variations of Co and Pd layer thicknesses in a bilayer stack exert a strong effect on the magnetic properties of the multilayer.[1] Such magnetic multilayers have been extensively explored as recording medium candidates for high density magnetic recording applications.[2-4] The perpendicular anisotropy is believed to arise from the hybridization of the d-shell electrons at the interfaces between the Co and Pd layers.[5,6]

EXPERIMENT

High anisotropy exchange-coupled (Co/Pd)N multilayers designed for bit-patterned medium applications were deposited using room temperature magnetron sputtering onto oxidized silicon substrates with a 5 nm Ta layer to diminish grain size and promote exchange coupling in the films[7]. The thicknesses of the Co and Pd layers and the deposition pressures were systematically varied to modify the magnetic properties of the films. The multilayers were patterned into large arrays of 200 nm islands using ion-beam proximity lithography, which has been described elsewhere[8]. The magnetic properties of continuous and patterned multilayers were evaluated using magneto-optical Kerr effect measurements. X-ray photoelectron spectroscopy (XPS) was used to evaluate the d-shell electron hybridization.

DISCUSSION

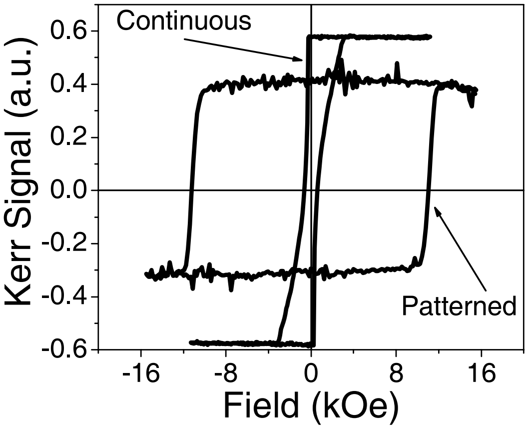
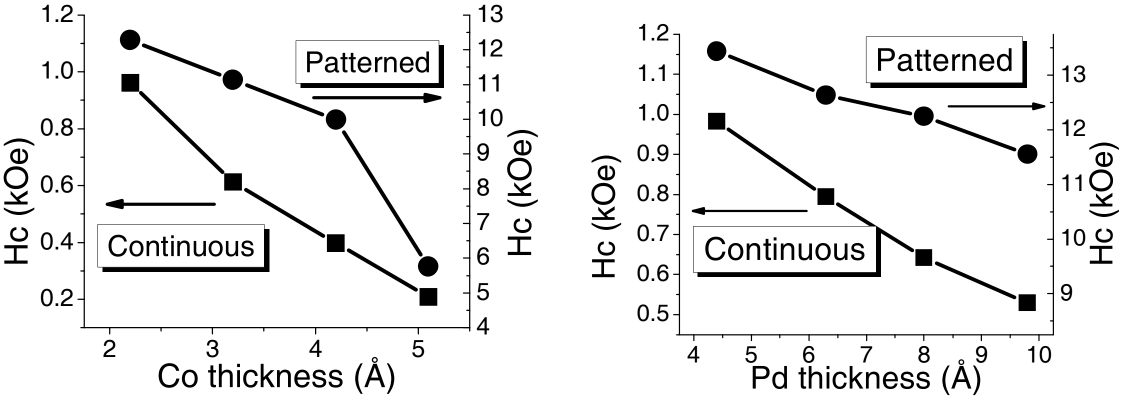


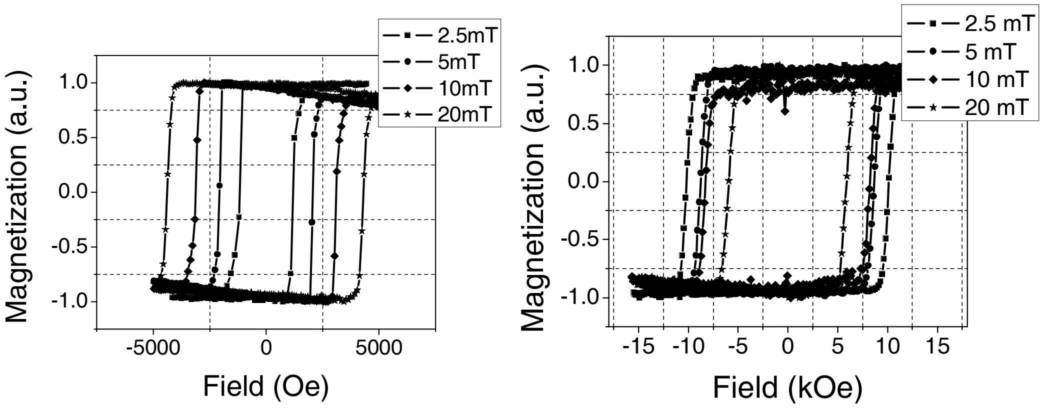
Figure 1. Vertical M-H loops for continuous and patterned (Co: 3 Å / Pd: 6 Å)$_{30}$ multilayers.



(a) **(b)**

Figure 2. Dependence of the coercivity, H_c, on (a) cobalt and (b) palladium layer thicknesses for continuous and patterned (Co/Pd)$_{30}$ multilayer films.

Vertical M-H loops for (Co: 3 Å / Pd: 6 Å)$_{30}$ multilayers having either continuous or patterned (200 nm islands) geometries are shown in Figure 1. The patterning leads to a significant increase in the coercivity due to the introduction of artificial domain wall pinning sites. Unlike domain wall nucleation and propagation in continuous films controlled by various defects and pinning sites, the bit geometry along with material parameters defines the domain wall nucleation fields in patterned films. Thus, the nucleation field and the coercivity of patterned films are good indicators of magnetic anisotropy as long as samples with the same island size are compared. The anisotropy in magnetic multilayers is a strong function of the Co and Pd layer thicknesses in the bi-layer stack as shown in Figure 2.



(a) **(b)**

Figure 3. Hysteresis loops for (Co: 2 Å / Pd 8 Å)$_{30}$ films (a) before and (b) after lithographic patterning.

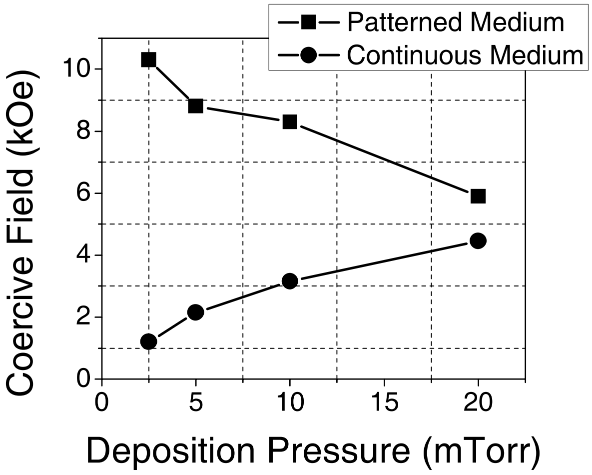
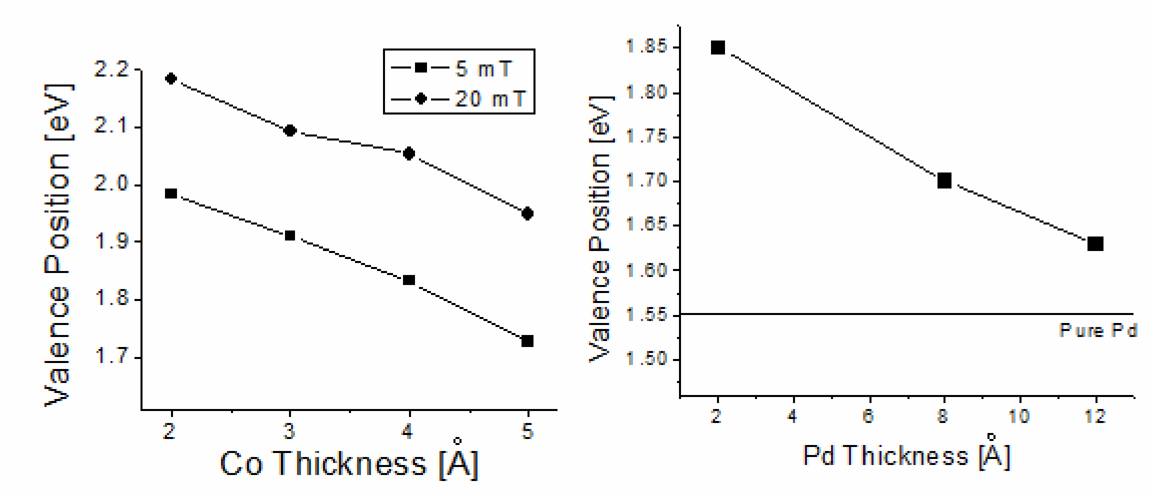


Figure 4. Coercivity as a function of deposition pressure for continuous and patterned (Co: 3 Å / Pd: 7 Å)$_{30}$ multilayer films.

Vertical M-H loops for a set of continuous and patterned [Co(2Å)/Pd(8Å)]$_{30}$ multilayer films deposited at different pressures are shown in Figure 3. The thicknesses of individual layers in the bilayer stack represent approximately one and two monolayers for Co and Pd, respectively, and are the optimal thicknesses for giving the highest perpendicular anisotropy. Although an increase in the coercivity is observed with increasing deposition pressures in the continuous films, the coercivity decreases after patterning as shown in **Figure 4**. This trend indicates that stronger perpendicular anisotropy is developed when the multilayers are deposited at lower pressures.

X-Ray Photoelectron Spectroscopy (XPS), which is commonly used to probe the binding energies and valence band positions of materials, was used to analyze the multilayer films. Since the typical probing depth of XPS is limited to about 2-3 nm, this technique can examine only the 1-2 topmost bilayers in the multilayer stacks prepared here. Nevertheless, assuming that there are no substantial anomalies arising from surface effects (*vide infra*), we can infer from these data the relevant details of the bandstructures of the entire films. The valence band data are located in the negative binding energy region, where the Pd 4d and Co 3d electrons can be probed.[9,10] The valence band peaks for pure Co and Pd samples appear at 2.5 eV and 1.6 eV, respectively. The XPS spectra of $(Co/Pd)_N$ multilayers are dominated by Pd signature, which enables to evaluate the hybridization of only the Pd 4d electrons.

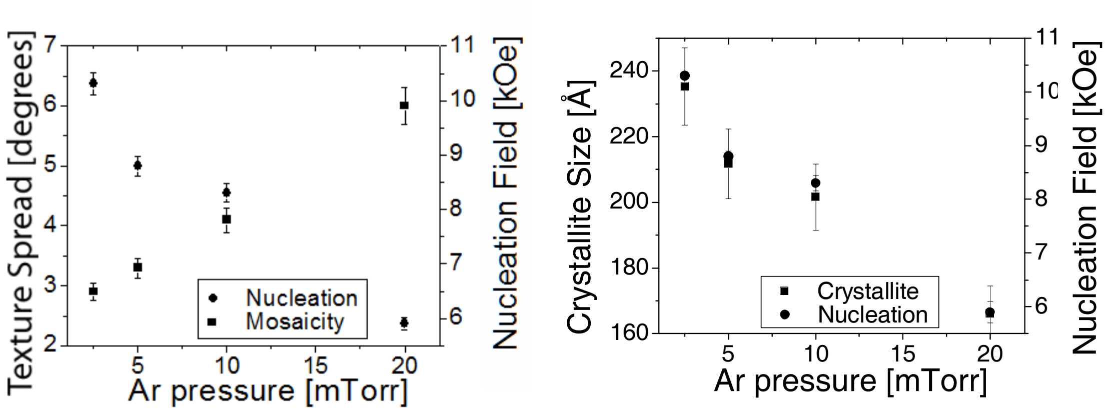


(a) **(b)**

Figure 5. (a) Valence position of the (Co: X Å / Pd: 7 Å)$_{30}$ films as a function of Co layer thickness and sputtering at two distinct deposition pressures; (b) Valence position of the (Co: 3 Å / Pd: X Å)$_{30}$ films sputtered at 2.5 mTorr.

The valence position of the multilayers as a function of Co thickness at two distinct deposition pressures is shown in **Figure 5**a. The decrease of the binding energy with increasing Co thickness correlates with the observed decrease in magnetic anisotropy with increasing Co thickness. Moreover, the binding energies for the 20 mT samples are significantly closer to the valence position of pure Co than pure Pd, which is in agreement with the decrease in anisotropy field of the samples with increasing deposition pressure. Weaker hybridization of the Pd atoms for samples with thicker Co layers and deposited at higher pressures leads to lower anisotropy. Significantly, no measurable d-electron hybridization was observed for as deposited CoPd alloys.

Pd atoms located further from the interface should experience less hybridization, and thus less magnetic moment than Pd atoms located immediately at the interface. XPS measurements will only yield an average for all of the layers within the probing depth of the material. Consequently, if the additional Pd monolayers are not hybridized as strongly as those at the interface, we would expect to see a drop in the valence position energy (closer to the position of pure Pd). Indeed, as the thickness of the Pd layer in the multilayer structure increases, the valence position shifts toward the Pd baseline sample as shown in **Figure 5**b. This observation is in agreement with ab initio calculations[6], which have shown that the Pd atoms nearest to the interface acquire a magnetic moment of $0.30\mu_B$ due to d-electron hybridization, whereas the second layer from the interface only $0.17\mu_B$, and the third layer $0.03\mu_B$.



(a) **(b)**

Figure 6. (a) Comparison of nucleation field values and film mosaicity for (Co: 2 Å / Pd: 8 Å)$_{30}$ films sputtered at various pressures; (b) Comparison of nucleation field values and crystallite size for (Co: 2 Å / Pd: 8 Å)$_{30}$ films sputtered at various pressures.

The dependence of the nucleation field values on the texture spread determined from the rocking curves is shown in Figure 6a. Lower deposition pressures give rise to better (111) textured films. While it has been reported that (111) texture might increase magnetic anisotropy[11], open questions remain regarding the role of crystallographic orientation in magnetic multilayers. We estimated the dependence of the nucleation field values in patterned multilayers on the average grain size using the Scherrer formula, $\langle L \rangle = \dfrac{K\lambda}{B_{1/2}\cos\theta_B}$, which is shown in Figure 6b. Similar to the effects of deposition pressure on film texture, lower deposition pressures give rise to larger grains. A lower number of defects per unit area (less grain boundaries) due to larger grain size likely contributes to the observed higher magnetic anisotropy values.

CONCLUSIONS

In summary, the magnetic properties of (Co/Pd)N magnetic multilayers have been correlated to XPS data and, in turn, to the deposition conditions and composition of the films. We found that samples with larger magnetic anisotropy exhibit strong shifts in the position of the Pd valence band -- a signature of d-shell electron hybridization. We also found that lower deposition pressures give films with greater anisotropy, which can be attributed to better crystallographic ordering and increased grain size (lower defects/grain boundaries per unit area).

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