Growth, structural, and magnetic properties of high coercivity Co/Pt multilayers

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Electron beam evaporated Co/Pt multilayers $\{[\mathrm{Co}(t_{\mathrm{Co}}\,\mathrm{nm})/\mathrm{Pt}(1\,\mathrm{nm})]_{10},\ 0.2<t_{\mathrm{Co}}<2\ \mathrm{nm}\}$ with perpendicular magnetic anisotropy and room temperature coercivities $H_c=2-15$ kOe are studied as a function of growth temperature T_G. Hysteresis loops and magnetic force microscopy (MFM) indicate changes in the magnetization reversal mechanism along with a sharp increase in coercivity for $T_G \gtrsim 230-250\,°\mathrm{C}$. Films grown at $T_G<230\,°\mathrm{C}$ ($t_{\mathrm{Co}}=0.2-0.4$ nm) show micrometer size magnetic domains and rectangular hysteresis indicating magnetization reversal dominated by rapid domain wall motion following nucleation at $H_n \sim H_c$. Films grown at $T_G>250\,°\mathrm{C}$ show fine-grained MFM features on the sub-100-nm length scale indicating reversal dominated by localized switching of small clusters. High-resolution cross-sectional transmission electron microscopy (TEM) with elemental analysis shows columnar grains extending throughout the multilayer stack. Co depletion and structural defects at the grain boundaries provide a mechanism for exchange decoupling of adjacent grains, which may result in the high coercivities observed. [DOI: 10.1063/1.1363602]

I. INTRODUCTION

High coercivity (12 kOe) perpendicularly oriented granular films on magnetically soft underlayers have been proposed as media for Terabit/in^2 areal density in magnetic recording.[1] A key requirement is a large ratio of coercivity and magnetization, which in Systeme International units should be about three.[2] Another requirement is a large negative nucleation field H_n and optimum shearing of the hysteresis such that the slope at the coercivity is mainly limited by demagnetization: $\alpha=4\pi dM/dH|_{Hc}\cong 1$.[3] CoX/Pt or CoX/Pd (X=Cr,B,Cu,Ag,...) multilayers are ideal candidates for this application owing to their large, interface-induced perpendicular magnetic anisotropy and tunability of structural and magnetic properties via growth conditions and CoX layer thickness.[4]

Here we show that growth induced grain boundary decoupling in Co/Pt multilayer films can lead to (a) large coercivity and large negative nucleation field, and (b) nearly perfectly sheared loops for recording applications. The key to achieving these properties is high temperature growth ($T_G \sim 300\,°\mathrm{C}$) which, however, has the adverse effect of grain growth. Observed grain diameters in the 30–80 nm range render the structures unattractive for perpendicular recording media. These results nonetheless provide insight into structural mechanisms leading to high coercivity and exchange decoupling in multilayer films in the absence of chemical segregants.

II. SAMPLE PREPARATION

The Co/Pt multilayer samples are fabricated by electron beam evaporation using a 10^{-8} Torr base pressure deposition system. They consist of a 20 nm Pt buffer layer, ten periods of Co (0.2–2.0 nm)/Pt (1 nm) bilayers, and a 1 nm Pt capping layer. Samples are grown on SiN_x (40 nm)-coated Si(001) substrates for magnetic and x-ray diffraction (XRD) studies and on electron transparent $\mathrm{Si_3N_4}$ windows for TEM studies (using a Philips CM200FEG). The SiN_x films are dc magnetron sputtered and the SiN_x-coated substrates are heated to $\sim 400\,°\mathrm{C}$ before deposition of the multilayers at growth temperatures $T_G=25-350\,°\mathrm{C}$. The Pt buffers are grown at fixed temperature, $T_G \cong 350\,°\mathrm{C}$. Growth rates are $\sim$0.05 nm/s for Co and Pt and the pressure during evaporation is in the low 10^{-7} Torr range. Magnetic hysteresis measurements are performed using polar and transverse Kerr techniques. Magnetic force microscopy (MFM) measurements are performed with a standard Digital Instruments, Inc. (D3000) microscope and Nanosensors GmBH & Co. pyramidal tips coated with CoCr.

III. MAGNETIC AND STRUCTURAL PROPERTIES

Hysteresis properties of a series of multilayers with $t_{\mathrm{Co}}=0.3$ nm were studied as function of the growth temperature: $25\,°\mathrm{C}<T_G<350\,°\mathrm{C}$. Results of perpendicular coerciv-

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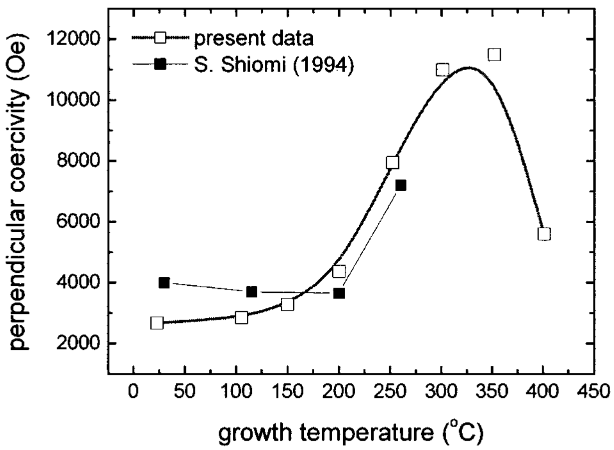

FIG. 1. Growth temperature dependence of the room temperature perpendicular coercivity of a series of $[Co(0.3\,nm)/Pt(1\,nm)]_{10}$ films. Data from Shiomi *et al.* (see Ref. 5) is given for comparison.

ity measurements are shown in Fig. 1 and compared with data from Shiomi *et al.*[5] The coercivity increases by more than a factor of 2 on increasing the T_G above ~220 °C. This increase is accompanied by marked changes in the hysteresis loops (Fig. 2). In addition, the as-grown domain state is observed via MFM to change from very coarse structured at low T_G, to very fine structured at high T_G (Fig. 3).

The low T_G films exhibit low initial susceptibility in the as-grown state, consistent with a well-pinned domain con-

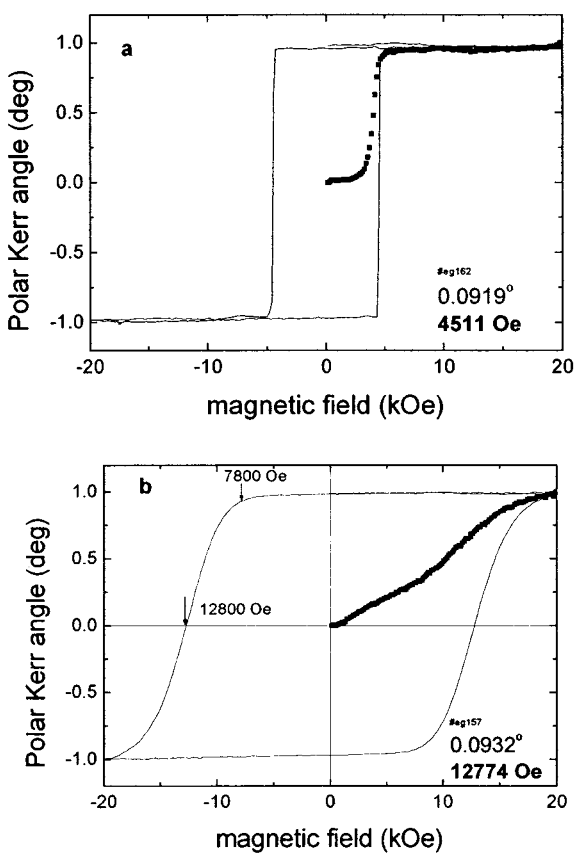

FIG. 2. Initial magnetization and hysteresis data for two $[Co(0.3\,nm)/Pt(1\,nm)]_{10}$ multilayer films evaporated at (a) $T_G \cong 210$ °C and (b) $T_G \cong 330$ °C; the initial magnetization curves are indicated by the large symbols.

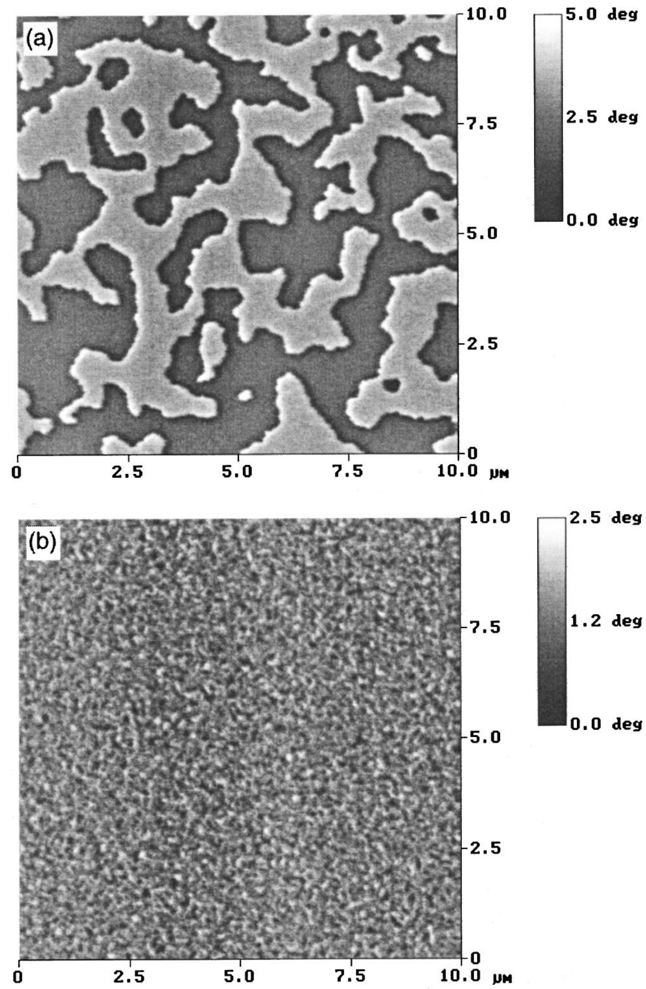

FIG. 3. The 10×10 μm phase-sensitive MFM images of samples grown at (a) $T_G \cong 220$ °C, and (b) $T_G \cong 350$ °C.

figuration. When the applied field H_a reaches a critical field for the domain walls to become unpinned, $H_p \sim 0.75 H_c$, there is a rapid increase in magnetization M until all walls are annihilated and saturation is reached. Upon reversal of the field, the field H_n required to nucleate a reverse domain is larger than H_p, and once nucleated, reversal of the entire film occurs very rapidly. These highly rectangular loops with $H_n \sim H_c$ may be expected in a structure in which reversal events are communicated throughout the film via strong exchange coupling between grains. For the high T_G films, on the other hand, in the as-grown state we see from the MFM data that there is a very fine domain structure, comprising small clusters of similarly oriented grains (interaction domains) with length scales below 100 nm. As a positive field is applied, the magnetization increases almost linearly with field. From this we surmise that these clusters reverse rather independently of their neighbors, consistent with an exchange-decoupled granular system.[6] After the films have reached saturation we find that demagnetization also takes place over a broad range of H_a, following onset at a substantial negative field we call H_r. The onset of reversal in Fig. 2(b) occurs at $H_r \cong 7.8$ kOe, and the sheared loop has $H_c = 12.8$ kOe. The hysteresis slope is $\alpha = 4\pi dM/dH|Hc \cong 1.5$.

Figure 4 shows high angle XRD measurements of

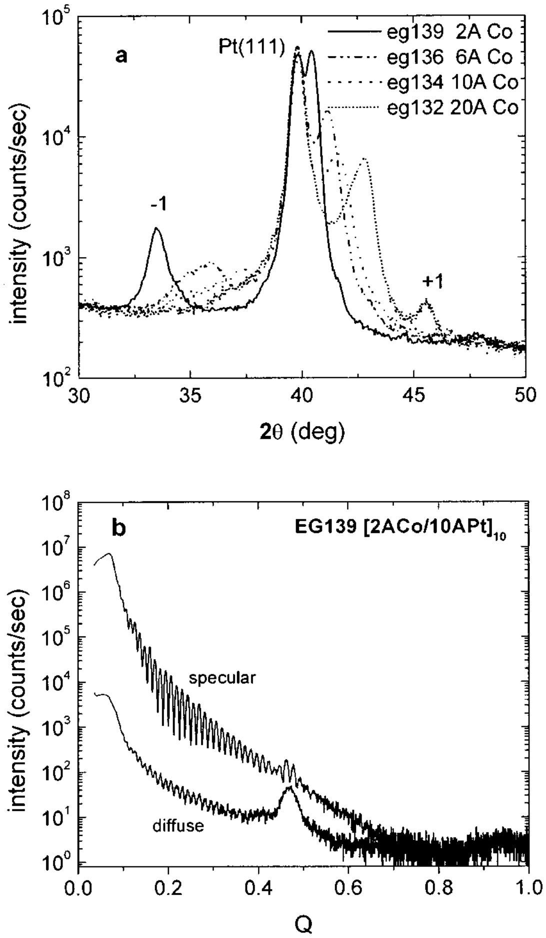

FIG. 4. (a) Specular $\theta-2\theta$ XRD measurements of $[\mathrm{Co}(t_{\mathrm{Co}})/\mathrm{Pt}(1\ \mathrm{nm})]_{10}$ multilayers grown at $T_G \cong 320\ ^\circ\mathrm{C}$ on 20 nm Pt ($0.2\ \mathrm{nm} < t_{\mathrm{Co}} < 2\ \mathrm{nm}$), and (b) specular and off specular (diffuse) x-ray reflectivity spectra ($t_{\mathrm{Co}} = 0.2$).

$[\mathrm{Co}(t_{\mathrm{Co}})/\mathrm{Pt}(1\ \mathrm{nm})]_{10}$ multilayers with Co-layer thickness, $0.2\ \mathrm{nm} < t_{\mathrm{Co}} < 2.0\ \mathrm{nm}$, grown at $T_G \cong 320\ ^\circ\mathrm{C}$. The high angle data show a large Pt(111) peak arising from the 20 nm Pt buffer and a CoPt(111) peak due to lattice averaging of Co and Pt that shifts to higher angles with increasing Co content. The films are (111) textured with rocking curve widths of the CoPt(111) peak of order 9°.[7] In addition, first order multilayer reflections arising from the periodic structure are observed. Even the structure with the thinnest Co layer of nominally one atomic layer ($t_{\mathrm{Co}} \sim 0.2$ nm) shows sharp, separated Pt(111) and CoPt(111) reflections with sharp multilayer reflections indicating a layered structure with coherent interfaces. A grazing incidence scan of the specular and diffuse x-ray intensity[8] of that film is shown in Fig. 4(b). A clear multilayer peak is not observed in the specular scan. However, the diffuse reflectivity, the scattered intensity obtained a few degrees off the specular reflection condition, displays a clear multilayer reflection. The presence of the ''Bragg'' peak in the diffuse background but not in the specular scan arises from correlated roughness in the multilayer. The lack of a specular peak indicates that the films are rather rough. This roughness, which increases with growth temperature, is also seen in atomic force microscopy (AFM).[9] The roughness is conformal from one layer to the next and the layering still exists on a finite lateral length scale.

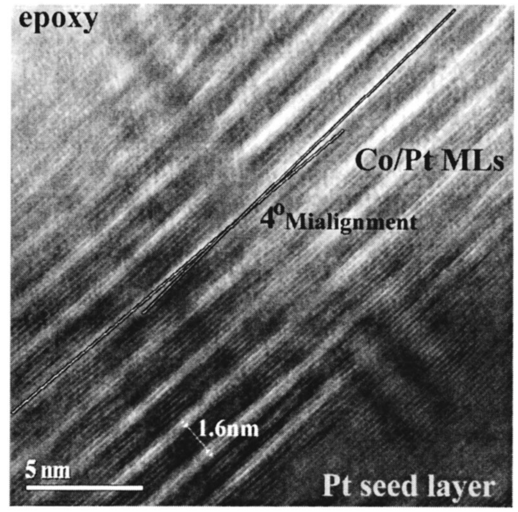

FIG. 5. High-resolution cross-sectional TEM image of a $[\mathrm{Co}(0.6\ \mathrm{nm})/\mathrm{Pt}(1\ \mathrm{nm})]_{10}$ multilayer grown at $T_G = 310\ ^\circ\mathrm{C}$.

The grain growth is columnar with grains propagating through the film thickness. High-resolution transmission electron microscopy (HRTEM) cross-sectional images show Co to be coherent with the Pt layers for this Co thickness. For increasing Co thickness, coherency loss is observed, and thick Co layers (above ~1.5 nm) show hcp stacking. High temperature samples show increased overall roughness and misalignment of the columns. Figure 5 shows a representative HRTEM image of a Co/Pt ML grown at 310 °C. The misalignment of two adjacent columns is shown to be 4°, however larger angles were also observed. For lower growth temperatures this feature is not found. The Co layers appear to be discontinuous across the boundary region. Energy filtered images showed similar Co-layer discontinuity at the grain boundary.[10]

ACKNOWLEDGMENTS

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