Perpendicular magnetic anisotropy and magnetic domain structure of unpatterned and patterned Co/Pt multilayers

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Abstract

Perpendicular magnetic anisotropy and magnetic domain structure were studied in epitaxial $[\text{Co}(t_{Co})/\text{Pt}(10 \text{ Å})]_{30}$ ($t_{Co} = 2, 2.5, 3, 4, 5 \text{ and } 10 \text{ Å}$) multilayers prepared on $\text{Al}_{2}\text{O}_{3}(11-20)$ substrate via Mo or Pt seed layer. The best perpendicular magnetic effect occurred for $t_{Co} \sim 3 \text{ Å}$. At remnant state the domain size tends to increase as $t_{Co}$ decreases, and the domain structure depends strongly on the seed layer. For $[\text{Co}(3 \text{ Å})/\text{Pt}(10 \text{ Å})]_{30}$ multilayers grown on gold grid made hole arrays, the polar coercivity inside the holes is different from those on the gold land and unpatterned area. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Large perpendicular magnetic anisotropy (PMA), high Kerr rotations and small stable recording bit are the key issues for high-density data storage in magneto-optical (MO) recording technology [1–3]. Co/Pt multilayers (MLs) are of particular interest for their strong PMA and Kerr effects at short wavelength [4]. Reduced dimensionality of the magnetic layers (to a few monolayers) together with the symmetry breaking in the interfaces (the so-called surface or interface anisotropy) of the multilayers can result in the change of magnetization from in-plane to perpendicular configuration. In addition, the interfacial structure such as the interfacial roughness or alloy formation may also play a significant role in deciding the PMA effect [5–7]. It was also demonstrated that the crystal orientation plays an important role in PMA of the Co/Pt MLs. For instance, (1 1 1) oriented Co/Pt MLs exhibit much enhanced PMA effect compared to (1 0 0) and (1 1 0) samples [1,8]. In this paper we focus more on the influence of the Co layer thickness and seeding layer on magnetic domain structure and PMA of (1 1 1) oriented $[\text{Co}(t_{Co})/\text{Pt}(10 \text{ Å})]_{30}$ MLs. For Co/Pt MLs grown on patterned substrate, the domain structure and domain reversal behavior inside and outside the patterned area will be discussed.

2. Sample preparations and characterizations

The patterned Co/Pt MLs were directly grown on pre-formatted sub-micrometer gold grids made on Si substrate by using thermal evaporation and e-beam lithography technique. The unpatterned Co/Pt MLs were grown on epitaxial-grade $\text{Al}_{2}\text{O}_{3}(11-20)$ substrates via Pt or Mo seed layer. The Co/Pt MLs studied here (both on patterned or unpatterned substrates) were prepared by a Vacuum Product molecular beam epitaxy system (MBE 930). Details of the chamber in which crystal
growth took place are provided elsewhere [9,10]. The base pressure of the MBE system was about $2 \times 10^{-10}$ Torr. During deposition of the Co/Pt MLs, the growth pressure was controlled below $5 \times 10^{-9}$ Torr and the deposition rates at $\sim 0.05$–$0.1$ Å/s. All the Co/Pt (unpatterned and patterned) samples studied here were grown at $\sim 100^\circ$C to avoid interfacial diffusion and maintaining good crystalline quality.

The polar $M$–$H$ loops of the Co/Pt MLs were studied by extraordinary Hall effect (EHE) and vibrating sample magnetometer (VSM). The EHE and VSM measurements were carried out at room temperature in a magnetic field $H$ up to 12 kOe. Magnetic domain structures of the Co/Pt MLs were observed by employing a polar Kerr microscope and a magnetic force microscope (MFM). The Co/Pt MLs were demagnetized prior to the

![Hysteresis Loops](image)

Fig. 1. Extraordinary Hall effect hysteresis loops of $[\text{Co}(t_{Co})/\text{Pt}(10 \text{ Å})]_{30}$ multilayers grown on Pt(200 Å)/Mo(200 Å) seeding layer on Al$_2$O$_3$(1 1 2 0) substrate; $t_{Co} = 10, 5, 4, 3, 2.5$ and 2 Å for (a), (b), (c), (d), and (e), respectively. The magnetic field was applied perpendicular to the film plane.
MFM study. The magnetic tip with a CoCr-coated Si tip magnetized along the tip axis was used to scan the magnetic domain structures in the MFM tapping-lift mode. Domain images represent the detected frequency shift of the vibrating cantilever. It has been shown that MFM contrast can be associated with up- and down-magnetized domains [11]. The films were first saturated in one perpendicular direction and then a reverse field near the nucleation field (slightly smaller than the coercive field) was applied and kept constant. The Kerr microscope was employed to monitor the development of the magnetic domains during the demagnetization process. Once the magnetic domains were developed, the samples were moved to the MFM stage for further study.

3. Results and discussions

3.1. Unpatterned Co/Pt multilayers

Fig. 1(a)–(f) show the EHE hysteresis loops of (1 1 1)-oriented \([\text{Co} (t_{\text{Co}})/\text{Pt}(10 \text{ Å})]\)\(_{30}\) MLs grown on Pt(200 Å)/Mo(200 Å) seeding layers on Al\(_2\)O\(_3\) (1 1-2 0) substrates. The EHE measurements indicate that the best polar coercivity and loop squareness occur at \(t_{\text{Co}} \sim 3\ \text{Å}\), in good agreement with the PMOKE results [5]. By VSM measurements of the out-of-plane- \((M_z)\) and in-plane- \((M_{\|})\) magnetization loops, the effective magnetic anisotropic constants \((K_{\text{eff}})\) of the \([\text{Co} (t_{\text{Co}})/\text{Pt}(10 \text{ Å})]\)\(_{30}\) MLs were estimated from the following equation [12]:

\[
K_{\text{eff}} = \frac{1}{V} \int_0^{H_{\text{sat}}} (M_z - M_{\|}) \, dH,
\]

where \(V\) is the total Co volume in the Co/Pt multilayers and \(H_{\text{sat}}\) the magnetic field to saturate the magnetization. By plotting \(t_{\text{Co}} \times K_{\text{eff}}\) as a function of the Co thickness \(t_{\text{Co}}\) (see Fig. 2), we obtained the interfacial (surface) anisotropic constant as \(K_s \sim 0.1\ \text{erg/cm}^2\) and the bulk anisotropic constant \(K_v = 3 \times 10^7\ \text{erg/cm}^3\) according to the relation

\[
t_{\text{Co}} \times K_{\text{eff}} = 2K_s + t_{\text{Co}} \times K_v.
\]

The \(K_{\text{eff}}\) values in this work are somewhat smaller than those reported [13,14] earlier by the other group.

Fig. 3(a)–(c) display the typical magnetic domains of the \([\text{Co} (t_{\text{Co}})/\text{Pt}(10 \text{ Å})]\)\(_{30}\) MLs with \(t_{\text{Co}} = 5, 4, 2.5\) and \(2\ \text{Å}\) for (a), (b), (c), and (d), respectively.

Fig. 2. \(t_{\text{Co}} \times K_{\text{eff}}\) plotted as a function of the Co thickness \(t_{\text{Co}}\). The effective anisotropic constant \(K_{\text{eff}}\) is defined in the text.
Fig. 4. MFM images scanned from [Co(3 Å)/Pt(10 Å)]$_{30}$ multi-layers grown on (a) 200 Å Pt(1 1 1) and (b) 200 Å Mo(110) seeding layer on Al$_2$O$_3$(1 1-2 0) substrate.

It has also been demonstrated that the crystal structure and magnetic anisotropy of the epilayers can depend strongly on the underlying seeding layer [15]. We study here the effect of seeding layer on the magnetic domain structure. Fig. 4(a)–(c) display the MFM images of the (111) oriented [Co(3 Å)/Pt(10 Å)]$_{30}$ MLs grown on the Al$_2$O$_3$(11-20) substrate with 200 Å Pt (111) and 200 Å Mo(110) seed layer, respectively. To our surprise, although the crystal quality and PMA effect in these two cases are pretty much the same, they show however very different domain structure. For Co/Pt sample grown on Mo seed layer no jagged domains were observed (Fig. 4(b)) and the average domain size is much larger than that grown on Pt seeding layer (Fig. 4(a)). Furthermore, the Mo seed layer produces markedly domain boundary anisotropy (Fig. 4(b)). This is possibly due to the anisotropic defects such as twins in the Co/Pt MLs resulted from the Mo seed layer, as suggested by X-ray diffraction [16].

3.2. Patterned Co/Pt multilayers

In an effort to understand domain reversal behavior of magneto-optical thin films in diminutive patterned region, we grew [Co(3 Å)/Pt(10 Å)]$_{30}$ MLs on gold grid made sub-micron hole arrays. Fig. 5(a) shows an example of such hole arrays with each hole area of ~ 0.25 μm × 0.25 μm and depth (gold grid thickness) of ~ 150 Å. The domain structure and reversal behavior of the Co/Pt MLs inside and outside the patterned area were studied by magnetic force microscopy (MFM) in the same scanned region by varying perpendicular magnetic field to the films.

This patterned sample was first saturated in one polar direction by applying a polar magnetic field of ~ − 7 kOe (minus sign defined as field directed into the film plane). The applied field was then increased in the reverse direction (directed out of the film plane) and allowed to approach the coercive field. Fig. 5(b)–(d) displays the MFM image by applying a polar magnetic field $H_p$ up to 1.8, 2.7 and 3.6 kOe, respectively. Fig. 5(b) showed that the magnetic moments in some area inside the patterned region reverse for $H_p$ ~ 1.8 kOe, while most of the moments outside the patterned region remained downward. For $H_p$ ~ 2.7 kOe, the moments reversal were complete on top of the gold land and occurred in most of the unpatterned area, while less than half of the holes the moments remained unchanged. This suggests that at low field ($H_p$ ~ 1.8 kOe) the moments reversal events occur chiefly on the gold land instead of inside the holes. Finally, for $H_p$ ~ 3.6 kOe the moments reversal were also complete at the unpatterned area and almost so in the holes. The MFM results indicate that the polar coercivity of the Co/Pt MLs inside the holes is somewhat larger than those on the gold land and unpatterned region for this case. However, in a systematic study of the patterned Co/Pt MLs, we found that the coercivity inside the holes does depend on the details of the holes. The domain reversal behaviors in patterned Co/Pt multilayers as a function of the hole shape, size, and depth will be reported in future publications.

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Fig. 5. (a) AFM pattern scanned from [Co(10 Å)/Pt(10 Å)]_{30} multilayers grown on gold grid made hole array; (b), (c), and (d) the corresponding MFM images scanned from the same region by applying a perpendicular magnetic field of 1.8, 2.7 and 3.6 kOe, respectively. The scanned region is 10 μm x 10 μm in each figure.

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