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Improvement of Perpendicular Magnetic Properties by Postannealing for M′–CoCrPt–M Stacked Media (M, M′ = Ti, Ta, Ru, Pt, CrMn, MnSi)

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***Abstract*—In this paper, we discuss the effect of postannealing on magnetic properties and microstructure for CoCr-based perpendicular recording media. Material investigation for cap- and under-layers of the postannealed media is carried out, and significant improvement of magnetic properties is confirmed for the media with both titanium cap- and under-layers. This is caused by decoupling of magnetic exchange interaction among grains due to diffusion of Ti into the grain boundaries and by elimination of the nanocrystalline initial layer that behaves like a soft magnetic layer.**

***Index Terms*—CoCr-based perpendicular media, exchange coupling, postannealing, titanium.**

I. Introduction

To REALIZE well-defined nonferromagnetic grain boundaries among magnetic grains for CoCr-based perpendicular media, several attempts, especially postannealing, have been made with the aim of diffusion of nonferromagnetic element from under- or cap-layer into the grain boundaries. According to several reports, it is pointed out that the postannealing enhances coercivity of the media [1]–[3]. However, the origin of the enhancement is still under discussion; some reports concluded that it is due to the diffusion of nonferromagnetic Cr [1] and/or Mn [2] atoms, and the other considered it be due to the elimination of the initial growth layer in the magnetic layer [3]. However, the most suitable material for cap- and under-layers and the mechanism of the improvement of the magnetic properties for the postannealed media have not yet been clarified. In this paper, we show the results of material investigation for cap- and under-layers, and we discuss the origin of the improvement of media properties by analyzing the microstructure and the intrinsic magnetic properties of the postannealed media.

II. Experimental Procedure

The media were fabricated by dc magnetron sputtering method on crystallized glass disk substrates, using the so-called ultraclean sputtering system [4]. The sputtering was made under Ar pressure of 0.6 Pa. The composition of the magnetic layer was fixed at Co_{68}–Cr_{16}–Pt_{16}. The nominal thickness of the magnetic layer $(d_{\mathrm{mag.}})$ was 30 nm except as otherwise noted. Various materials were utilized as the under-layer (Ti, Ta, Pt, or Ru) and the cap-layer (Mn_{50}–Si_{50}, Cr_{50}–Mn_{50}, Ru, or Ti). The thickness of the under-layer and the cap-layer was 25 and 5 nm, respectively, except for the Ru (5 nm) under-layer prepared on Ti (25 nm) seed-layer. The disks were heated by an infrared lamp run by constant power without exposure to the atmosphere. The substrate heating was performed up to 300 °C just after the deposition of the under-layer. The postannealing was carried out up to 410 °C for 13 s just after the deposition of the cap-layer. The magnetization curve and perpendicular magnetic torque curve were evaluated by polar Kerr equipment, vibrating sample magnetometer (VSM), and torque magnetometer, respectively. The saturation magnetization (M_{s}) and uniaxial magnetocrystalline anisotropy of columnar grains $(K_{\mathrm{u}}^{\mathrm{grain}})$ were determined from the $M_{\mathrm{s}}^{\mathrm{exp.}} \times d_{\mathrm{mag.}}$ versus $d_{\mathrm{mag.}}$ plot and the $K_{\mathrm{u}\perp}^{\mathrm{exp.}} \times d_{\mathrm{mag.}}$ versus $d_{\mathrm{mag.}}$ plot; $M_{\mathrm{s}}^{\mathrm{exp.}}$ and $K_{\mathrm{u}\perp}^{\mathrm{exp.}}$ correspond to the experimentally obtained total saturation magnetization and total perpendicular magnetic anisotropy of the whole film, respectively [5], [6]. The microstructure was examined by cross-sectional and plane-view transmission electron microscopy (TEM). The composition analysis was performed by energy dispersive X-ray spectroscopy attached to TEM (TEM-EDX) utilizing an electron beam with a diameter of about 2 nm.

III. Result and Discussion

A. *Effect of Postannealing on Magnetic Properties for M′–CoCrPt–M Media*

Fig. 1(a)–(c) shows typical Kerr loops for postannealed (solid line) and nonannealed media (broken line) with stacking structure of CoCrPt–Pt, CoCrPt–Ti, and Ti–CoCrPt–Ti, respectively. The stacking structure, coercivity (H_{c}), and squareness (S) for the postannealed and nonannealed media are listed in Table I. Under-layer materials which produce c axis out-of-plane orientation in magnetic layers were investigated first (media A-D in Table I). In the case of epitaxially grown media with Pt or Ru under-layer, H_{c} and S were degenerated by annealing. In the case of the media with Ta or Ti under-layer, which have a nanocrystalline initial layer in the magnetic layer just after deposition [5], the change in magnetic properties by annealing was completely different. Annealing lead to decrement of H_{c} for the

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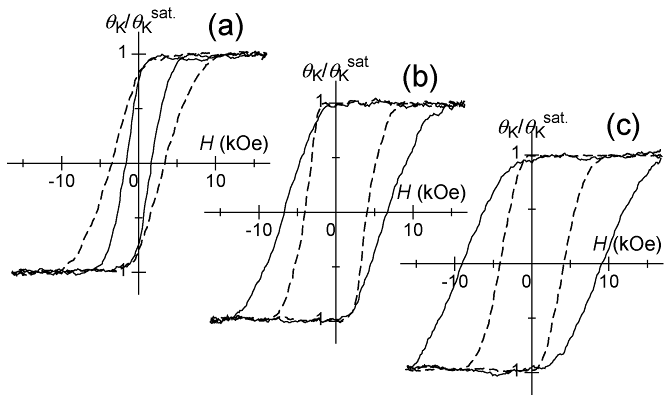

Fig. 1. Kerr loops for media with (a) Pt under-layer, (b) Ti under-layer, and (c) Ti cap- and under-layer, respectively. Solid and broken lines correspond to annealed and nonannealed media, respectively.

TABLE I
COERCIVITY H_c AND SQUARENESS S FOR NONANNEALED AND ANNEALED MEDIA WITH STACKING STRUCTURE OF CAP–COCRPT–UNDER

	materials of layer		non-annealed		annealed	
	under-layer	cap-layer	H_c (kOe)	S	H_c (kOe)	S
A	Ti	-	4.0	1.0	6.7	1.0
B	Ta	-	3.9	1.0	3.0	1.0
C	Pt	-	3.4	0.8	1.6	0.8
D	Ru/Ti	-	4.3	0.8	3.4	0.8
E	Ti	$Mn_{50}Si_{50}$	4.0	1.0	6.9	0.8
F		Ru	4.0	1.0	7.4	1.0
G		$Cr_{50}Mn_{50}$	4.0	1.0	7.9	1.0
H		Ti	4.0	1.0	9.1	1.0

media with Ta under-layer; on the other hand, H_c drastically increases from 4.0 to 6.7 kOe for the medium with Ti under-layer. To obtain further increment of H_c, cap-layer materials were investigated for postannealed media utilizing Ti under-layer. As seen in Table I (media E-H), cap-layers except for Mn_{50}–Si_{50} were found to be effective to enhance H_c. Especially, the media with Ti cap-layer showed remarkable improvement of H_c up to 9.1 kOe. Therefore, among materials examined in this study, Ti was found to be the most efficacious as cap- and under-layer material for postannealed media. Further investigation revealed that these layers could be thinned down to 1 nm for cap- and 5 nm for under-layers, respectively, in order to enhance H_c [7]. We have been working to further reduce the underlayer thickness, which is required to reduce the spacing losses.

B. Change in Microstructure by Postannealing for Ti–CoCrPt–Ti Media

Fig. 2(a) and (b) shows bright-field images obtained by cross-sectional TEM for nonannealed and annealed media, respectively, with the stacking structure of Ti–CoCrPt–Ti. For the medium (a), a layer structure with light gray contrast can be seen on Ti under-layer, suggesting the formation of the nanocrystalline initial layer, and that the magnetic layer grows on it [5]. On the other hand, for the medium (b), four stacked layers can be clearly observed. TEM-EDX and XRD analyses revealed that the four layers correspond to Ti (hcp), TiCoPt (B2), CoCrPt (hcp), and TiCoPt (B2) layers from the substrate side. It should be noted here that no initial layer

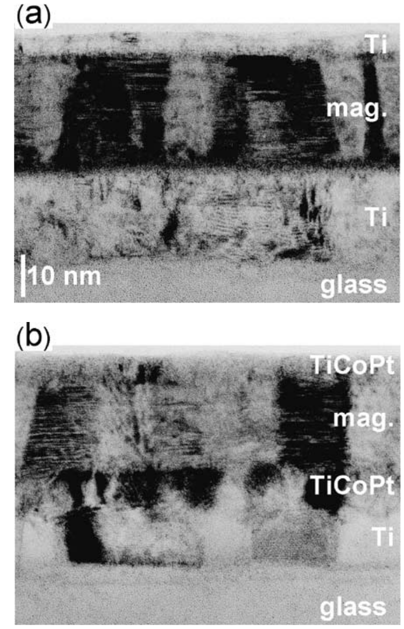

Fig. 2. Bright-field images obtained by cross-sectional TEM for (a) nonannealed and (b) annealed Ti–CoCrPt–Ti media.

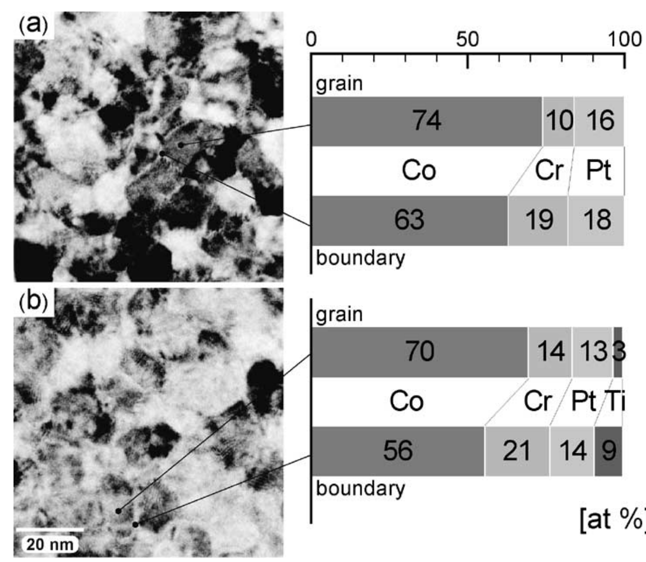

Fig. 3. (left) Bright-field images of magnetic layer obtained by plane-view TEM and (right) histograms for Co, Cr, Pt, and Ti elements contained by grain or boundary obtained by TEM-EDX for (a) nonannealed and (b) annealed media, respectively.

consisting of nanocrystalline grains can be seen in CoCrPt layer. These facts indicate that the Ti layer and the magnetic layer react and form nonferromagnetic TiCoPt layer at the interface, resulting in perfect elimination of the nanocrystalline initial layer which behaves as soft magnetic layer and degrades magnetic properties of the medium [8].

Fig. 3(a) and (b) shows bright-field images obtained by plane-view TEM for nonannealed and annealed media, respectively, with the stacking structure of Ti–CoCrPt–Ti. The respective composition analysis result of the grain and the grain boundary are shown at the right side. To analyze the magnetic layer, the Ti layer and TiCoPt reacted layer were removed by ion milling. Each composition was determined as

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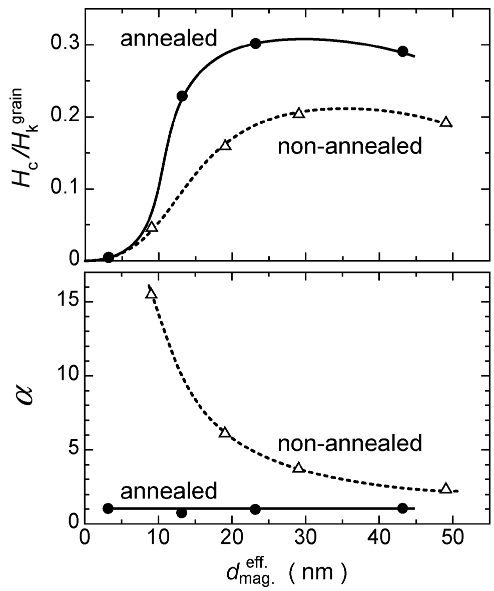

Fig. 4. (Top) Hysteresis loop slope parameter α and (bottom) normalized coercivity H_c/H_k^{grain} as a function of the effective thickness of magnetic layer $d_{mag.}^{eff.}$. Solid and broken lines correspond to annealed and nonannealed media, respectively.

the average value of thee different regions, though only one point was indicated in a bright-field image. For both the media (a) and (b), the content of nonferromagnetic elements in the grain boundary is found to be larger than that in the grain. In the grain boundary, the total content of nonferromagnetic elements is 44 at.% for the medium (b), which is larger than 37 at.% for the medium (a). Furthermore, the Ti content in the grain boundary is 9 at.% for the medium (b) in contrast with 0 at.% for the medium (a). Therefore, for the Ti–CoCrPt–Ti postannealed media, it is suggested that the grain boundaries tend to become nonferromagnetic due to diffusion of Ti from the cap- and under-layers.

Finally, we discuss the decoupling of magnetic exchange interaction among grains taking the results of structural analyses into account. Fig. 4 shows the hysteresis loop slope parameter $(\alpha = 4\pi|dM/dH|_{H=H_c})$ and the normalized coercivity (H_c/H_k^{grain}) as a function of magnetic layer thickness. Solid and broken lines correspond to annealed and nonannealed media, respectively. The abscissa axis displays the effective ferromagnetic layer thickness of the magnetic layer $(d_{mag.}^{eff.})$, which is equal to $d_{mag.} - d_{mag.}^{dead.}$; $d_{mag.}^{dead.}$ is the thickness of nonferromagnetic region formed in CoCrPt layer. With decreasing magnetic film thickness, α becomes larger for the nonannealed media, whereas α shows a constant value of 1 for the annealed media. In general, for perpendicular recording media, intergranular exchange coupling through the soft magnetic initial layer contributes to large α in the thin magnetic film region [9]. Our present results suggest the elimination of the initial layer, which is in good agreement with the result of the structural analysis. Furthermore, taking account of the facts that α decreases down to 1 and H_c/H_k^{grain} increases by postannealing, we can conclude that postannealing decouples the intergranular exchange interaction in the media. Other analyses results [7], such as magnetic reversal volume, also support this conclusion.

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