Oblique-incidence sputtering of Ru intermediate layer for decoupling of intergranular exchange in perpendicular recording media

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(Presented 15 November 2010; received 23 September 2010; accepted 27 December 2010; published online 7 April 2011)

During the Ru deposition process for granular type perpendicular magnetic recording media, both a reduction in the Ru intermediate layer thickness and lowering of sputtering gas pressure were successfully achieved by focusing on a self-shadowing effect. Oblique-incidence sputtering with a 60° incident angle under an Ar gas pressure of 0.6 Pa yielded (1) columnar Ru grains with a growth direction of 30° from the film normal, (2) *c*-plane sheet texture by epitaxial growth on the Pt underlayer, and (3) a flat envelope of the surface and a deep gap at grain boundaries. This change in the Ru structure significantly contributes to reducing exchange coupling among magnetic grains, especially in the initial growth region in an overlying granular medium. © 2011 American Institute of Physics. [doi:10.1063/1.3562262]

I. INTRODUCTION

Currently, perpendicular magnetic recording media are composed of three functional parts: a soft magnetic underlayer (SUL), a nonmagnetic intermediate layer (NMIL), and a recording layer (RL). The NMIL plays an important role in providing nucleation and oxide precipitation sites for the magnetic isolation of the granular RL. To realize these roles, Ru with *c*-plane orientation and a topological bumped surface in the grain diameter period is widely used, induced by high-gas-pressure sputtering and film thickness of about 20 nm.¹⁻⁴ For further increases in the recording density, a key technological issue is the reduction in spacing loss between the recording head and the SUL, which can be effectively accomplished by thinning the Ru NMIL while retaining the crystalline orientation and surface morphology mentioned in the preceding text. In general, a high-gas-pressure process reduces the mean free path and changes the uniform flow direction of the sputtered atoms. Therefore the oblique-incidence angle effect during sputtering under a high gas pressure may mainly affect the formation of the topological bumped surface of Ru. In this study, to clarify the self-shadowing effect during film growth, oblique-incidence sputtering under a low-gas-pressure process was carried out.

II. EXPERIMENTAL PROCEDURES

All samples prepared in the present study were fabricated by direct-current (dc) magnetron sputtering onto 2.5-in glass substrates at room temperature. The stacking structure of the sample was substrate/Ta (5 nm)/Pt (6 nm)/Ru (5–20 nm)/C (7 nm). For a granular RL, Co₇₄Pt₁₆Cr₁₀-8 mol. % SiO₂ (16 nm) was deposited under an Ar gas pressure of 4.0 Pa on a Ru layer as required for the media. The oblique-sputtered Ru (Ru^{LP}_{Obl}.

hereafter) was deposited under an Ar gas pressure of 0.6 Pa for enhancing the self-shadowing effect. During the oblique sputtering, the incident angle of the sputtered atoms was fixed by using a shield with a 5-mm aperture placed between the substrate and target. Although the thickness of Ru at the wafer scale (2.5 in.) might not be uniform, in the selected region where incident angle is 60°, the thickness of Ru can be treated as uniform enough. For comparison, Ru was also deposited using the conventional facing configuration of the target to the substrate under Ar gas pressures of 0.6 and 8.0 Pa (Ru^{LP}_{Nor.} and Ru^{HP}_{Nor.}, respectively, hereafter). Other layers were also deposited using the conventional configuration. The crystalline structure of the samples was examined by x-ray diffraction (XRD), using Cu-K_α radiation, as well as transmission electron microscopy (TEM). During in-plane XRD measurements, the incident angle of the x-rays in XRD was fixed at 0.4°, and thus the profiles reflect structural information at a depth of approximately 20 nm from the film surface. The physical grain diameter of the granular film was estimated from the full width at half maximum (FWHM) of the in-plane XRD profile using Scherrer's equation. The magnetic properties were measured using polar Kerr equipment (PKE) and a vibrating sample magnetometer (VSM). The activation volume V_{act} , which corresponds to the coherent magnetic reversal volume in a medium, was determined by irreversible susceptibility measurements using the equation $V_{act} = (kT)/(M_s H_f)$, $H_f = [dH_r(t)/d \ln(t)]^5$, where H_f is the fluctuation field, T is the absolute temperature, and k is Boltzmann's constant.

III. RESULTS AND DISCUSSION

A. Microstructure of oblique-incidence sputtered Ru film

Figure 1 shows XRD profiles for the Ru^{LP}_{Obl.} films with the out-of-plane [Fig. 1(a)] and in-plane [Fig. 1(b)] configurations. Only diffraction lines from the (00.2) plane in Fig. 1(a) and the

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FIG. 1. (Color online) (a) Out-of-plane and (b) in-plane XRD profiles for the sub./Ta/Pt/Ru^{LP} film.

(10.0) plane in Fig. 1(b) are observed in the examined range of 2θ , which indicates a highly oriented c -plane sheet texture of the present Ru film even fabricated by the oblique sputtering. Figure 2 shows a pole figure of (00.2) diffraction for the Ru^{LP} film. The black region indicates an area with no data due to instrumental causes. α and ϕ correspond to the tilted angle from the film normal and the rotational angle in the film plane, respectively. Any clustering of (00.2) diffraction is not observed in the pole figure except in the film normal direction displayed, where $\alpha = \phi = 0^\circ$. Thus there were few grains with c axis parallel to the incident direction of the sputtered atoms. Figure 3 shows a bright field cross-sectional TEM image of the Ru^{LP} film. For the TEM observations, the sample was processed to face the plane includ-

FIG. 2. (Color online) Pole figure of (00.2) diffraction from Ru for the sub./Ta/Pt/Ru^{LP} film. (The Bragg angle is fixed at 42.2° during measurement.) The black region indicates an area with no data due to instrumental causes.

FIG. 3. Typical cross-sectional TEM image for the sub./Ta/Pt/Ru^{LP} film. (a) Entire view of the sample. (b) Enlarged view near the interface between the Ru and Pt layers.

ing the film normal and the incident direction of sputtered atoms. Columnar Ru grains were formed with the growth direction tilted 30° from the film normal. Focusing on the upper part of the Ru layer, deep gaps are observed at the grain boundaries. It is thus clearly confirmed that a self-shadowing effect occurred. In contrast, an initial growth region with a thickness of 5–7 nm is present, wherein adjacent Ru grains contact each other at the bottom of the Ru layer. The close-up inset in Fig. 3 shows the enlarged microstructure near the interface between the Ru and Pt layers. Lattice stripes parallel to the film plane continue from a Pt grain to a Ru grain. These lattice fringes were confirmed to be the (111) plane of Pt and the (00.2) plane of Ru. Therefore it was safely concluded that obliquely grown Ru grains could possess c -plane sheet texture due to epitaxial growth on Pt grains. It should be noted that the envelope of the surface of the Ru^{LP} layer is flat. This feature can also be listed as an advantage of the present proposed oblique-incidence sputtering under a low-gas-pressure process from the viewpoint of stabilizing the float and reducing the float height of the head in the hard disk drive. Figure 4 shows a cross-sectional TEM image of the granular RL deposited on the Ru^{LP} layer. In Fig. 4(a), many white streaks are seen along the film's normal direction in the granular layer. This indicates that the growth direction of the magnetic grains is vertical in the granular layer. This is quite reasonable, considering the facing configuration of the target to the substrate. Figure 4(b) shows an enlarged view near the interface between the Ru^{LP} and granular layers. The lattice stripes corresponding to (00.2) planes of hcp-Ru and Co-based magnetic grains continue at the interface in spite of the difference in growth direction of Ru and magnetic grains. Thus magnetic grains grow vertically from the film plane on the obliquely grown Ru and possess c -plane sheet texture due to epitaxial growth.

B. Magnetic properties of the media deposited on oblique-incidence sputtered Ru film

Figure 5 shows perpendicular hysteresis loops for media using Ru_{Nor.}^{LP}, Ru_{Nor.}^{HP}, and Ru_{Obl.}^{LP} nonmagnetic intermediate layers with a thickness of 20 nm. Compared with the medium using a Ru film deposited under low-gas-pressure, hysteresis of the medium using the Ru_{Obl.}^{LP} film is larger than that using the Ru_{Nor.}^{LP} film due to oblique-incidence sputtering. In addition, this hysteresis is also larger than the medium using the Ru_{Nor.}^{HP} film, which is widely used in the production of current media. Figure 6(1) shows the Ru thickness (d_{Ru}) dependence

FIG. 4. Cross-sectional TEM image for the medium with the stacking structure of the sub./Ta/Pt/Ru^{LP}/granular RL. (a) Complete view of the sample. (b) Enlarged view near the interface between the granular and Ru layers.

of the saturation field (H_s), coercivity (H_c), and nucleation field (H_n) of granular media deposited on the three types of Ru layer mentioned in the preceding text. H_n scarcely changes, and H_s , H_c increase with increasing d_{Ru} for each of the media. To evaluate the degree of magnetic decoupling of the media, two indexes, the loop slope at coercivity (α) and the normalized activation volume (V_{act}/V_{grain}) were derived as a function of d_{Ru} . In the medium using the Ru^{LP}_{Obl.} film, both α and V_{act}/V_{grain} decrease with increasing d_{Ru} and V_{act}/V_{grain} approaches about 2. Moreover, α and V_{act}/V_{grain} of the media using the Ru^{LP}_{Obl.} film have the smallest values among the media using the conventional Ru intermediate layer. Thus it is found that an oblique-incidence sputtered Ru can promote exchange decoupling among the magnetic grains of the granular layer. An interesting point is that α and V_{act}/V_{grain} of the medium using the Ru^{LP}_{Obl.} film remain almost constant through the 10–20 nm Ru thickness. Thus we found that the Ru intermediate thickness can be reduced to 10 nm by using the present proposed oblique-incidence sputtering.

FIG. 5. (Color online) Perpendicular hysteresis loops for media using Ru^{LP}_{Nor.} (dotted line), Ru^{HP}_{Nor.} (dashed line), and Ru^{LP}_{Obl.} (solid line) nonmagnetic intermediate layers.

FIG. 6. (Color online) Change in (1) H_s , H_c , and H_n and (2) α and V_{act}/V_{grain} as a function of d_{Ru} .

C. Correlation between microstructure of Ru film and exchange decoupling of overlaying media

Finally, the mechanism of exchange decoupling of the granular media is discussed in relation to the unique microstructure of the obliquely grown Ru. Oblique-incidence sputtering under a low-gas-pressure process was found to enhance the self-shadowing effect; this results in deep gaps with wide spaces for the column boundaries. In the first stage of the granular layer deposition, because the oxide is well segregated at the Ru layer gap, magnetic grains can grow with one-on-one growth without contact with neighboring magnetic grains. It is considered that the noncontact part of the initial growth of the granular layer achieves good exchange decoupling among the magnetic grains. Concerning the present oblique-sputtering configuration, a self-shadowing effect occurred only along one specific direction. Therefore further exchange decoupling among the magnetic grains can be realized by applying self-shadowing effect to every direction.

ACKNOWLEDGMENTS

This study was supported by the Industrial Technology Research Grant Program in 2006 from the New Energy and Industrial Technology Development Organization of Japan (NEDO).

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