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Magnetic Properties and Domain Structure of $SmCo_5$ Perpendicular Magnetization Films Prepared by Using a UHV Sputtering System

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The effects of the thicknesses of a Cu/Ti underlayer and a Sm-Co layer on the magnetic properties and domain structure of $SmCo_5$ perpendicular magnetization films prepared by using an ultra-high-vacuum sputtering system were investigated. By adjusting the thicknesses of both the Cu/Ti underlayer and the Sm-Co layer, the coercivity was controlled to be a moderate value, allowing the films to be used in magnetic recording media while maintaining a squareness ratio of unity. As the Sm-Co layer thickness was reduced, the magnetic cluster size decreased and the magnetization reversal process varied from wall motion mode to a rotation mode. It is suggested that the Cu-rich region in the initial growth stage of the Sm-Co layer functions as the pinning site of the magnetic domain wall and plays an important role in controlling the magnetic domain structure.

Key words: $SmCo_5$ thin film, perpendicular magnetic anisotropy, magnetic domain structure, magnetization reversal process, UHV sputtering

1. Introduction

Thin films composed of permanent magnet materials attract much attention in the field of magnetic devices because they are expected to be applied to a magnetic recording medium and a minute magnet for micro-electro-mechanical systems (MEMS). Especially, thin films exhibiting high perpendicular magnetic anisotropy, used as magnetic recording media, are urgently required for achieving an ultra high recording density [1].

A $SmCo_5$ alloy is a representative permanent magnet and has extremely strong uniaxial magnetocrystalline anisotropy, whose anisotropy constant, K_u, is more than 1.1 x 10^8 erg/cm^3 [2]. Many researchers have studied on $SmCo_5$ thin films with in-plane magnetic anisotropy [3-5]. On the contrary, a $SmCo_5$ thin film exhibiting perpendicular magnetic anisotropy had not yet been prepared. Recently, we have developed a sputter-deposited $SmCo_5$ thin film exhibiting distinct perpendicular magnetic anisotropy by introducing a relatively thick Cu underlayer, whose thickness was 100 nm or more [6]. Takei *et al.* also reported a similar result [7]. Moreover, we found that the perpendicular magnetic anisotropy was markedly enhanced by using a Cu/Ti dual underlayer [8].

However, there are serious problems for practically applying the $SmCo_5$ thin films to perpendicular magnetic recording media. One is that the thick Cu underlayer was necessary for generating high perpendicular magnetic anisotropy [9, 10], which led to a large magnetic spacing loss between a soft magnetic underlayer in a double-layered medium and a writing head. For instance, it is said that total thickness of a recording layer and an underlayer (intermediate layer) should be reduced to 18 nm for accomplishing the areal recording density of 600 Gbit/inch^2 [11]. Another is that the coercivity, H_c, and the saturation field, H_s, caused by the high perpendicular magnetic anisotropy are too large to write recorded bits by using currently available recording heads [12]. In the present circumstances, it is hard for a recording medium with such high values of H_c and H_s more than 10 kOe to be saturatedly recorded.

In this study, effects of thicknesses of the Cu/Ti underlayer and the Sm-Co layer on magnetic properties of $SmCo_5$ thin films prepared using an ultra high vacuum (UHV) sputtering system were again investigated as trials to solve the above-mentioned problems. In addition, the domain structures and the magnetization reversal processes of these films were experimentally examined.

2. Experimental

The films prepared in this study consisted of Sm-Co (8-25 nm)/Cu (0-200 nm)/Ti (0-50 nm)/glass disk. An amorphous carbon overcoat was deposited upon the Sm-Co layer as a protective layer. Based on our previous study [13], the Sm-Co layer was formed by laminating Sm (0.31 nm) and Co (0.41 nm) sublayers alternately. The thickness ratio of Sm and Co sublayers produced the Sm-Co layer with an atomic composition equal to $Sm_{24}Co_{76}$, which was measured with inductively coupled plasma atomic emission spectroscopy. Here, the composition is defined as that in the deposit of Sm-Co layer only. The Cu diffusion from the Cu underlayer to the Sm-Co layer was not taken into consideration [10]. Thus, the actual Sm content was likely to be lower than 24 at%. From an x-ray diffractometry, it was confirmed that (00ℓ) reflections of the hexagonal $SmCo_5$ phase were clearly observed in the films exhibiting distinct perpendicular magnetic anisotropy, namely, its *c* axis (direction of magnetization easy axis) was oriented in the perpendicular direction. On the other hand, reflections of the other Sm-Co intermetallic phases were not observed.

The films were prepared using a UHV dc magnetron sputtering system. The base pressure in the sputtering chamber was 1.5 x 10^{-9} Torr or lower, unless otherwise stated. The Ar gas pressure during the deposition of each layer was adjusted at 1.5 mTorr. The substrate temperature was set at 20 °C for the deposition of underlayers, followed by the deposition of the Sm-Co layer at 225 °C.

Magnetic properties of the films were measured using a vibrating sample magnetometer with the maximum applied field (H_{max}) of 15 kOe. The magnetization state was observed by using a magnetic force microscope (MFM). The magnetic cluster size was defined as a correlation length where the value of autocorrelation function for the MFM image at an ac-demagnetized state was zero. Compositional distributions of the films along the growth direction were evaluated with an Auger electron spectrometer (AES).

3. Results and discussion

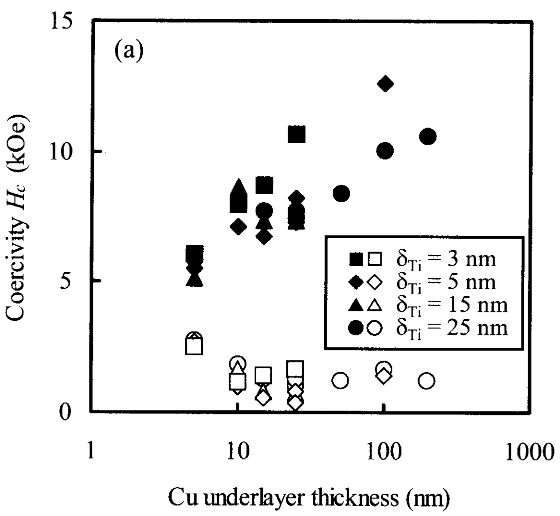
3.1 Magnetic properties

Figs. 1 (a) and (b) show dependencies of H_c and squareness ratio, SQR, on the Cu underlayer thickness of the films consisting of Sm-Co (25 nm)/Cu (*x* nm)/Ti (3, 5, 15, 25 nm)/glass disk, respectively. Here, the SQR was defined as a ratio of remanent magnetization to the magnetization measured in the easy axis at the H_{max} of 15 kOe. The value of H_c in the direction perpendicular to the film plane monotonously increased with the Cu underlayer thickness. The SQR in the perpendicular direction was almost unity for the films with a Cu underlayer of 10 nm or more in thickness. In other words, by reducing the Cu underlayer thickness down to 10 nm, the value of H_c can be decreased with keeping the SQR of unity.

Figs. 2 (a) and (b) show the dependencies of H_c and SQR on the Ti underlayer thickness of the films consisting of Sm-Co (25 nm)/Cu (10, 25 nm)/Ti (*y* nm)/glass disk. The value of H_c did not strongly depend on the Ti underlayer thickness. Films with excessively thick Ti underlayer, which was thicker than Cu underlayer, did not tend to exhibit the SQR of unity. In this study, the Cu/Ti thickness ratio of approximately 3-4 was found to be preferable for high perpendicular magnetic anisotropy resulting in the SQR of unity. For instance, the value of K_u for the film consisting of Sm-Co (25 nm)/Cu (10 nm)/Ti (3 nm)/glass disk was as large as 3.8 x 10^7 erg/cm^3.

As in our previous studies [10], when the Cu underlayer was completely removed, the distinct perpendicular magnetic anisotropy was not generated in Sm-Co thin films. The Ti underlayer was also indispensable to obtain the smooth film surface and to promote the preferred orientation of the *c* axis of $SmCo_5$. Therefore, it is again confirmed that the Cu/Ti dual underlayer is effective to prepare $SmCo_5$ thin films with high perpendicular magnetic anisotropy.

In addition, the coercivity was found to be dependent on the thickness of the Sm-Co layer. Fig. 3 shows *M-H* hysteresis loops for the films consisting of Sm-Co (8, 10, 15 nm)/Cu (5 nm)/Ti (2 nm)/glass disk, whose values of H_c in the perpendicular direction were 4.6, 7.2, and 8.0 kOe, respectively. In this case, the thinner Sm-Co layer further decreased the value of H_c because of the deterioration of perpendicular magnetic anisotropy



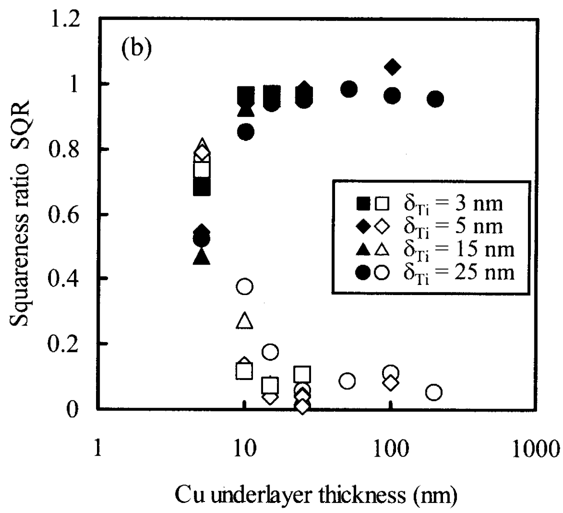


Fig. 1 Dependencies of the coercivity and squareness ratio on the Cu underlayer thickness of films consisting of Sm-Co (25 nm)/Cu (*x* nm)/Ti (3, 5, 15, 25 nm)/glass disk. Solid and open symbols represent the values in the directions perpendicular and parallel to the film plane, respectively.

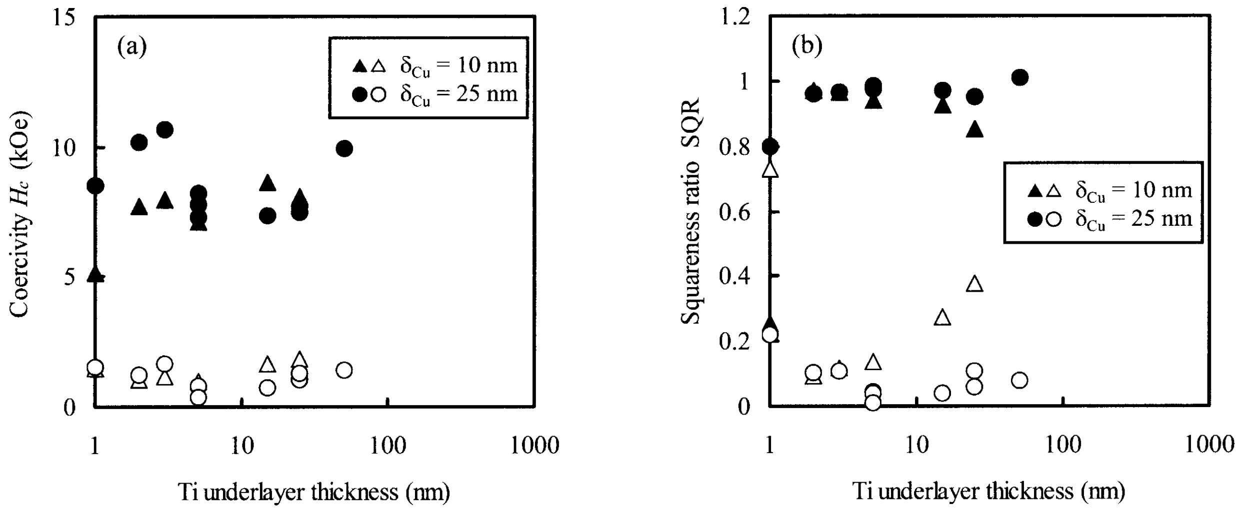


Fig. 2 Dependencies of the coercivity and squareness ratio on the Ti underlayer thickness of films consisting of Sm-Co (25 nm)/Cu (10, 25 nm)/Ti (y nm)/glass disk. Solid and open symbols represent the values in the directions perpendicular and parallel to the film plane, respectively.

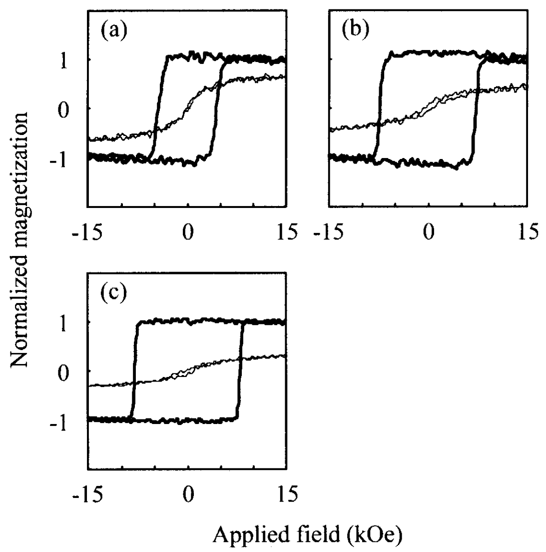


Fig. 3 *M-H* hysteresis loops (a), (b), and (c) are for films of Sm-Co (8, 10, 15 nm)/Cu (5 nm)/Ti (2 nm)/glass disk, respectively. Thick and thin lines represent loops in the directions perpendicular and parallel to the film plane, respectively.

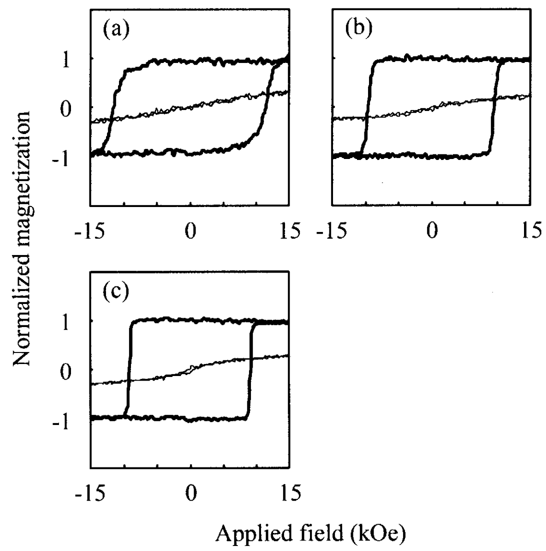


Fig. 4 *M-H* hysteresis loops (a), (b), and (c) are for films of Sm-Co (8, 10, 15 nm)/Cu (10 nm)/Ti (3 nm)/glass disk, respectively. Thick and thin lines represent loops in the directions perpendicular and parallel to the film plane, respectively.

inferred from the shapes of *M-H* loop in the film plane. On the other hand, the values of H_c for the films consisting of Sm-Co (8, 10, 15 nm)/Cu (10 nm)/Ti (3 nm)/glass disk were 11.6, 9.5, and 9.1 kOe, respectively as shown in Fig. 4; the reduction of the Sm-Co layer thickness increased the value of H_c. In this case, the higher value of H_c was likely to be dominated by that in magnetization reversal process mentioned afterward.

In our previous study [12], we pointed out that in order to apply the $SmCo_5$ thin films to magnetic recording media, the total film thickness, especially the Cu underlayer thickness, should be further reduced and magnetic properties, especially excessively large values of H_c and H_s more than 10 kOe should be appropriately decreased. From the results in Figs. 1, 3, and 4, the value of H_c varied from several kilo Oersted to upwards of ten kilo Oersted by adjusting the thicknesses of both the Cu/Ti underlayer and the Sm-Co layer. In a certain case, the values of H_c and H_s managed to be a moderate value with maintaining the SQR of unity while reducing the total film thickness. This is useful for applying the $SmCo_5$ thin films to perpendicular magnetic recording media in a conventional recording system.

Fig. 5 shows the relationship between the SQR for the films consisting of Sm-Co (25 nm)/Cu (10 nm)/Ti (3 nm)/glass disk and the base pressure in the sputtering

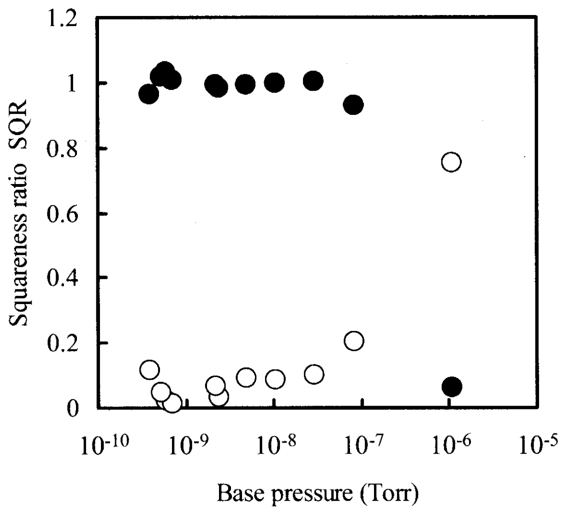


Fig. 5 Relationship between the squareness ratio for films of Sm-Co (25 nm)/Cu (10 nm)/Ti (3 nm)/glass disk and the base pressure in the sputtering chamber before deposition of the films.

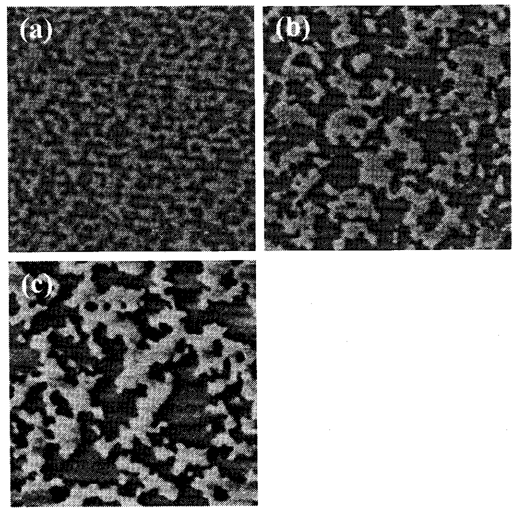


Fig. 6 MFM images in the ac-demagnetized state of the films in Fig. 3. (a), (b), and (c) are for the Sm-Co layer thickness of 8, 10, and 15 nm, respectively. The scan area is 5 μm square for each film.

chamber before depositing them. Each film was prepared in the same sputtering chamber. A low base pressure less than 10^{-7} Torr markedly increased the SQR in the perpendicular direction and decreased that in the film plane. We have reported that a thick Cu underlayer more than 100 nm was necessary for obtaining high perpendicular magnetic anisotropy in the films prepared using a conventional HV sputtering system with a base pressure around 10^{-7} Torr [10]. This result suggests that the UHV environment is so effective to generate high perpendicular magnetic anisotropy even in the films with a thin Cu/Ti underlayer. However, it is unclear why the UHV environment is effective. To elucidate the effect of the UHV environment, the analysis of atomic scale microstructure should be carried out. The microstructural study by means of an AES and a high resolution transmission electron microscope is now in progress.

3.2 Domain structures and magnetization reversal processes

It is important that magnetic domain structures and magnetization reversal processes of the developed $SmCo_5$ thin films would be clearly understood, prior to the examination as magnetic recording media. Fig. 6 shows MFM images at the ac-demagnetized state for the films in Fig. 3. The magnetic domain wall of these films was deeply indented, suggesting that the pinning effect against the wall movement was strong. The shape of the initial magnetization curve for each film was convex downward, supporting the conjecture that the magnetization reversal process was dominated by the wall pinning [14]. The thinner the Sm-Co layer was, the smaller the magnetic cluster size was: For the film with 8 nm-thick Sm-Co layer, the magnetic cluster size was 119 nm.

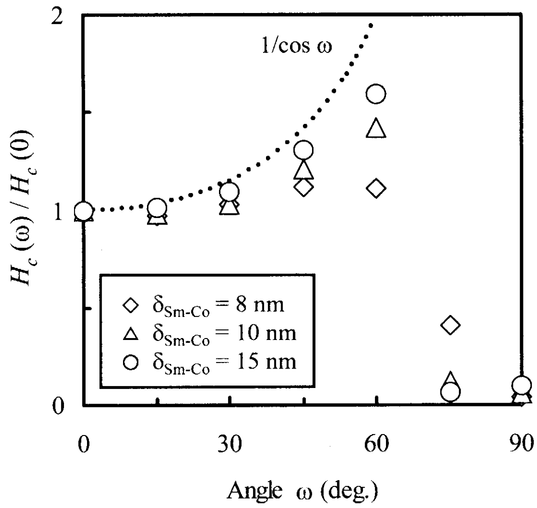


Fig. 7 Dependency of the coercivity of the films in Fig. 3 on the angle of the applied field from the direction perpendicular to the film plane. The dotted line represents the dependency in the case of the ideal wall motion mode.

Fig. 7 shows the dependency of H_c for the films in Fig. 3 on the angle of the applied field from the direction perpendicular to the film plane. Here, the demagnetization field was not compensated. Magnetization was almost saturated in each angle smaller than 60 deg. The angular dependency of coercivity for the film with the Sm-Co layer of 15 nm in thickness almost conformed to the equation of $H_c(\omega) = H_c(0)/\cos\omega$. This indicates that the wall motion mode is dominant in the magnetization reversal process. The

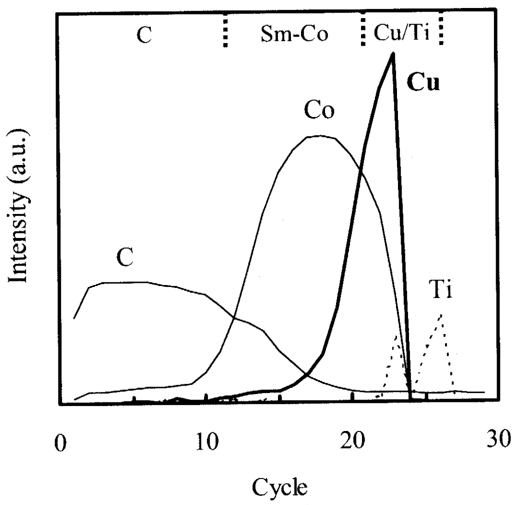


Fig. 8 AES depth profiles of a film consisting of Sm-Co (15 nm)/Cu (5 nm)/Ti (2 nm)/glass disk.

magnetization reversal process gradually became close to a rotation mode with the reduction of the Sm-Co layer thickness. This change is consistent with that of magnetic cluster size; namely, the magnetic cluster size was small in the film with the magnetization reversal process close to a rotation mode. In addition, the films with Cu (10 nm)/Ti (3 nm) underlayer in Fig. 4 showed much the same trend of the change in magnetic cluster size and magnetization reversal process as the Sm-Co layer thickness was varied.

Judging from the change in magnetic domain size and magnetization reversal process, the magnetic domain wall movement is considered to be restricted more strongly as the Sm-Co layer thickness became small. This suggests that the thinner the Sm-Co layer was, the stronger the pinning effect was. Fig. 8 shows AES depth profiles of the film consisting of Sm-Co (15 nm)/Cu (5 nm)/Ti (2 nm)/glass disk. Here, the profile of Sm is omitted because of its very weak intensity. It should be noted that the Auger electron intensity ratio in Fig. 8 did not represent the composition ratio among each element in the film. Especially, the profile of Ti did not necessarily represent accurate compositional distribution for the small thickness of the Ti layer and oxidation of Ti by oxygen contained in the glass substrate. The profiles indicate that Co and Cu atoms penetrated each other, namely, the Sm-Co layer and the Cu underlayer were interdiffused. The region containing a large amount of Cu atoms was formed in the initial growth stage of the Sm-Co layer. We assume that this peculiar region works as the pinning site of magnetic wall and plays an important role in restricting the magnetic wall movement. This is reasonable because the magnetic wall movement was restricted more strongly in the films with the thinner Sm-Co layer. We have already asserted that the Cu-rich region in the Sm-Co layer is essential for generating high perpendicular magnetic anisotropy [10]. The results in this study suggest that the Cu-rich region is also a key for controlling the magnetic domain structure of the $SmCo_5$ thin films exhibiting high perpendicular magnetic anisotropy.

4. Conclusion

Effects of thicknesses of Cu/Ti underlayer and Sm-Co layer on magnetic properties and domain structures of the $SmCo_5$ perpendicular magnetization films prepared using a UHV sputtering system were investigated. As a result, the moderate values of coercivity and saturation field for magnetic recording media were achieved in the film whose thickness was much smaller than that of the films in the previous study. Moreover, by reducing the Sm-Co layer thickness, the magnetization reversal process became close to a rotation mode even in the films where the wall pinning dominated the magnetization reversal process, and the magnetic cluster size became small. Therefore, we expect that further modification of layer configuration and preparation conditions leads to the practical application of $SmCo_5$ thin films to perpendicular magnetic recording media.

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