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Evaluation of inter-granular coupling in stacked perpendicular recording media

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Abstract

The trial for quantitative evaluation of inter-granular coupling in stacked perpendicular recording media is reported. The evaluation is realized by analyzing magnetic domain in relation with microstructure of the cap layer initial growth layer. When the thickness of cap layer is increased, the change of magnetic domain from single magnetic domain to maze magnetic domain can be observed. The critical thickness of the cap layer where the change happened was around 5.1 nm. According to this analysis, when granular layer and cap layer of stacked media are assumed to be single layer, inter-granular coupling with amount of around 2.9 erg/cm^2 was obtained which agrees with the simulation result qualitatively.

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Keywords: Stacked media; inter-granular coupling; initial growth layer; granular layer; cap layer; magnetic domain; energy barrier

1. Introduction

Stacked perpendicular recording media are considered to be the most promising method to realize high recording density of 1 Tbit/in^2 and more [1], [2], [3]. The media are composed of a granular layer and a cap layer. Generally, a-CoCrPt-oxide material with magnetically well isolated grains is used for granular layer. For the cap layer, layer with some amount of inter-granular coupling is used. Inter-granular coupling of the granular layer in these media are controlled through the cap layer [4]. Variation of the inter-granular coupling for the cap layer greatly influences magnetic properties of the media. Therefore quantification of inter-granular coupling in the cap layer is essential to understand the mechanism of magnetic properties change in the media. However, currently there is no detail report regarding the quantitative evaluation of the inter-granular coupling constant.

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In this paper, we reported the trial for quantitative evaluation of inter-granular coupling in cap layer and granular layer by analyzing magnetic domain of the stacked media with various cap layer thicknesses. The inter-granular coupling of the cap layer is considered to depend on the contact area between grains in the cap layer which is determined by the initial growth of column structure for the cap layer. Therefore, the microstructure model of stacked media derived from TEM observation result is also studied here.

2. Experimental procedure

All layers were fabricated on glass substrate at room temperature with DC magnetron sputtering system. The structure of the samples: Glass/Ta(5 nm)/Pt(6 nm)/Ru(20 nm)/Granular layer/Cap layer/COC(7 nm). $Co_{74}Cr_{10}Pt_{16}$-SiO_2 (8 mol%) (16 nm) with saturation magnetization (M_s) and magnetic anisotropy constant (K_u) values of around 640 emu/cm^3 and 5.2x10^6 erg/cm^3 was used as the granular layer. [Co(0.6 nm)/Pd(1.1 nm)]$_n$ multilayer with n varied from 0 to 9 were used for the cap layers. M_s and K_u values of the cap layer were around 580 emu/cm^3 and 4.1x10^6 erg/cm^3. Magnetic properties were extracted from *M-H* loop measured by VSM. K_u of each layers were measured by torque magnetometer for single layer with maximum applied field of 25 kOe. Microstructure observation of the media was carried out by TEM. Magnetic domain was observed with magnetic force microscopy (MFM) at AC erased state. The probe of MFM is coated with CoCrPt material.

In order to confirm the validity of this analysis method a simulation was conducted with LLG equations. Magnetic properties for the granular layer and cap layers are the same with above information. Inter-granular coupling constant inside the grain is assumed to be 100 erg/cm^2 [5]. Cubic magnetic grains with diameter of 10 nm are separated into small grids with 5 x 5 x 5 nm^3 size. Totally 128 x 128 columns were used in this calculation. Magnetic properties were simulated with various inter-granular coupling constant in the cap layer.

3. Result and discussion

3.1. Evaluation of inter-granular coupling in stacked media

3.1.1. Magnetic properties

Fig.1 shows coercivity (H_c) dependence on cap layer thickness for stacked media. At cap layer thickness of around 1.7 nm, H_c is around 4.2 kOe which is almost the same with granular media. When the thickness of cap layer is increased further, H_c starts to drop drastically.

Fig. 2 shows *slope* dependence on cap layer thickness for stacked media. When cap layer thickness is increased to 1.7 nm, *slope* (dM/dH at around H_c) [6] is almost constant at 2.7. In this region, it is shown that there is almost no inter-granular coupling in the cap layer. With further increase of cap layer thickness, *slope* of the media will increase monotonously which means larger inter-granular coupling. From this result, it is shown that the increase of inter-granular coupling of the cap layer will reduce H_c.

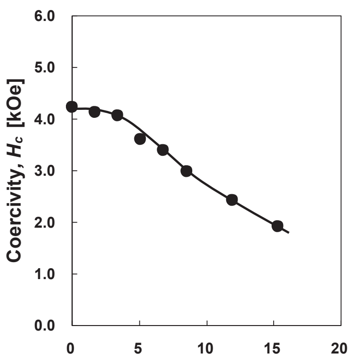


Fig. 1 Coercivity (H_c) dependences on cap layer thickness for stacked media.

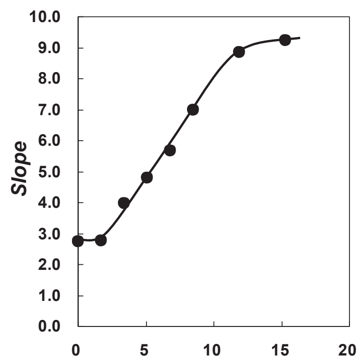


Fig. 2 *Slope* dependences on cap layer thickness for stacked media.

3.1.2. Microstructure of stacked media

Fig. 3 shows cross section and in-plane section TEM images of typical stacked media. In the cross section image, it is shown that one crystal grain of the cap layer grows on one crystal grain of the granular layer. In addition, the initial layer of cap layer only grows on metal part of granular layer. Grain boundary can be observed at initial layer of cap layer on the top of granular layer grain boundary. The grain boundary structure also can be observed in the in-plane section TEM image, with some grains at cap layer separated by grain boundary.

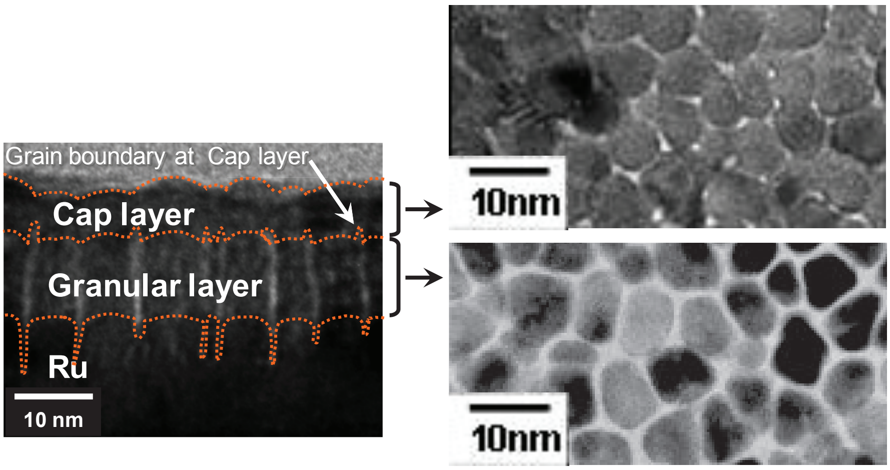


Fig. 3 Cross section and in-plane section and TEM images of typical stacked media

Fig. 4 shows the model for stacked media according to TEM observation result. Some part of the cap layer is in contact each other. The initial growth layer for the cap layer on the top of granular layer grain boundary consists of voids. When cap layer thickness is changed the thickness of cap layer which is in contact is changed that varies the inter-granular coupling constant.

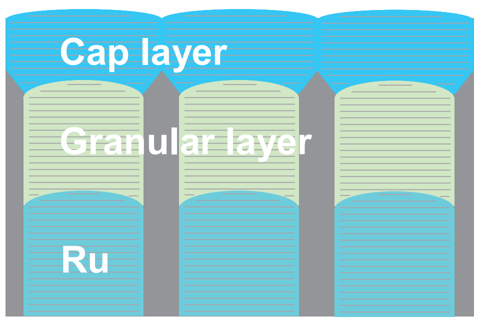


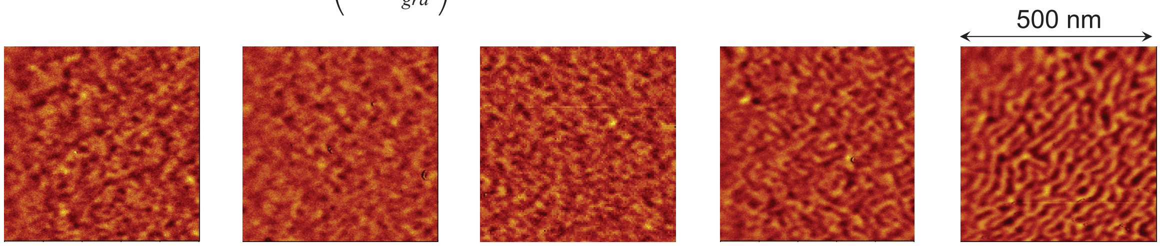
Fig. 4 Model for stacked media according to TEM observation result.

3.1.3. MFM analysis

Fig. 5 shows the magnetic domain observation done by MFM. All samples were AC-erased before the measurement. The result shows that when the thickness of the cap layer (CL) is increased at cap layer thickness of around 6.8 nm, the magnetic domain changed from single magnetic domain to maze magnetic domain. The thickness where the magnetic domain starts to change was defined as critical thickness (t_C). At this experiment we found t_C was around 5.1 nm. From this result, it is shown that the change of magnetic domain is affected by the change of inter-granular coupling of the cap layer. In order to find out the relation between t_C and inter-granular coupling constant in stacked media, analysis of total energy of the magnetization by using model is carried out.

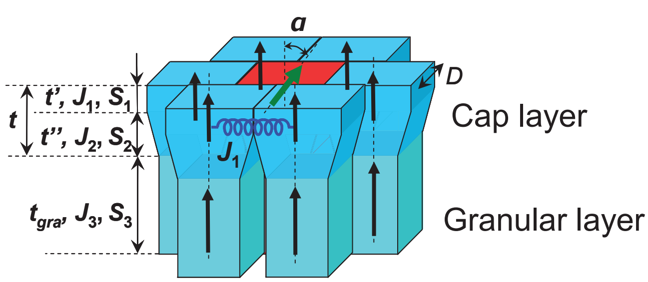
Fig. 6 shows the model of the crystal grains for stacked media. Fig. 6(a) shows the model of center grains surrounded with 6 grains for stacked medium with granular layer and cap layer. Fig. 6(b) shows stacked medium with single layer model which is equivalent to model in fig. 6(a). The center grain is also surrounded with 6 grains. In this image the front 2 grains and the behind 2 grains were taken out to focus on the center grain. The exchange coupling constant between center grain and neighbours of cap layer with side surface in contact and not in contact are shown with J_1 and J_2. The exchange coupling constant for granular layer is defined with J_3. J_2 and J_3 are equal to zero because the side surfaces of the grains do not contact each other. The side surface areas for cap layer with center grains in contact and not in contact with neighbors are shown with S_1 and S_2. The side surface area for granular layer is defined with S_3. Layer thickness of cap layer and granular layer are defined with t and t_{gra}. t consists of t' and t'' that show the thickness for cap layer with center grains in contact and not in contact with neighbors. When the cap layer and granular layer are assumed to be one rectangular grain, exchange coupling constant of the center grain (J_{ave}) with grain surface S can be expressed with following equation:

$$J_{ave} = \frac{S_1 J_1}{S} = \left(\frac{t'}{t + t_{gra}}\right) J_1 \tag{1}$$

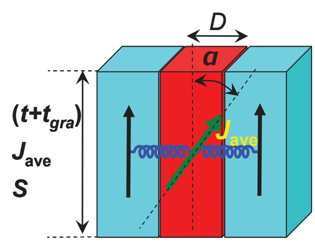


(a) CL: 0 nm (b) CL: 1.7 nm (c) CL: 3.4 nm (d) CL: 5.1 nm (e) CL: 6.8 nm

Fig. 5 Magnetic domain observation done by MFM.



(a) Model of center grains surrounded with 6 grains for stacked medium with granular layer and cap layer



(b) Stacked medium with single layer model which is equivalent to model in figure 6(a). The center grain is also surrounded with 6 grains. In this image the front 2 grains and the behind 2 grains were taken out to focus on the center

Fig. 6 The model of crystal grains for stacked media.

When the grain volume, magnetic anisotropy constant, saturation magnetization and angle between easy axis and magnetization of each grain shown in fig. 6(b) are expressed with v, $K_u^{ave.}$, $M_s^{ave.}$ and α, the total energy at applied field H for center grain which consists of magnetic anisotropy energy, Zeeman energy, demagnetization energy, exchange coupling energy can be expressed with following equation:

$$E = v[K_u^{ave}\sin^2\alpha - M_s^{ave}H\cos\alpha + 2\pi(M_s^{ave.})^2\cos^2\alpha] - J_{ave}S\cos\alpha \tag{2}$$

During the analysis the following conditions are assumed:

Magnetization at neighbor grains are fixed at easy axis,

Applied field, $H = 0$ (at AC-erase state)

From this assumption equation (2) can be simplified to equation (3)

$$E = v[K_u^{ave}\sin^2\alpha + 2\pi(M_s^{ave.})^2\cos^2\alpha] - J_{ave}S\cos\alpha \tag{3}$$

When the demagnetization field energy in equation (3) is ignored it can be simplified into equation (4) and the plot between energy and angle can be shown in fig. 7.

$$E = vK_u^{ave} \sin^2 \alpha - J_{ave} S \cos \alpha \quad (4)$$

From this plot, it is shown that during the rotation of magnetization at center grain from 0 degree easy axis to 180 degrees easy axis, the maze magnetic domain can be observed when the magnetization of center grain is in parallel direction with magnetization of neighbour grains. On the other hand, when magnetization of center grain is anti parallel with magnetization of neighbour grains, single domain will be observed. According to the total energy, the critical condition where maze magnetic domain is observed can be determined when energy barrier $\triangle E$=0. At this condition the thickness of cap layer will be t_C.

With the same idea, to solve $\triangle E$=0 for total energy which include the demagnetization field energy (equation (3)), numerical calculation with below parameters was carried out.

t: 5.1 nm, t_{gra}: 16 nm, M_s^{ave}: 625 emu/cm^3, K_u^{ave}: 4.9x10^6 erg/cm^3, J_1: 100 erg/cm^2 [5], D: 10 nm

M_s^{ave} and K_u^{ave} are calculated by weight averaging the M_s and K_u of granular layer and cap layer by thickness of granular layer and cap layer at critical cap layer thickness. D shows the average grain diameter when the grain of granular layer and cap layer is assumed to be one grain. From the calculation result, J_{ave}: 2.9 erg/cm^2 can be obtained. When this result is substituted into equation (1), t': 0.6 nm can be obtained.

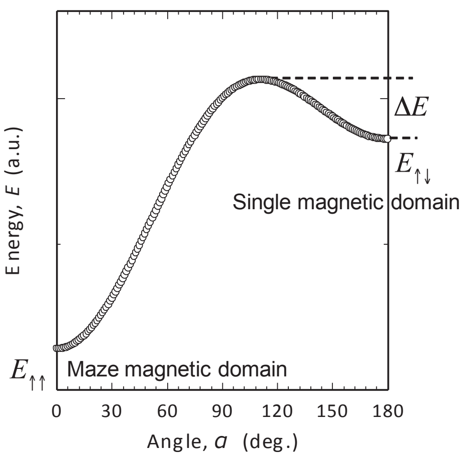


Fig. 7 Energy dependence on rotation angle.

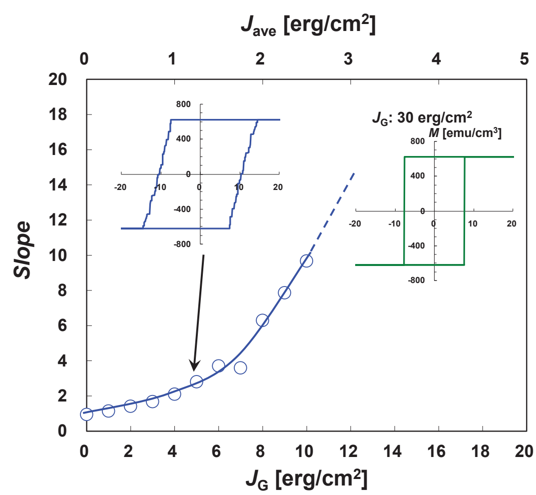


Fig. 8 Magnetic simulation result.

3.2. Simulation of stacked media with various inter-granular coupling in the cap layer

In order to confirm the validity of this analysis method some simulation was conducted with LLG equations. Fig. 8 shows the result of magnetic simulation. In this simulation J_G is used to express the exchange coupling in the cap layer. This parameter is the weight average of J_1 and J_2 by thickness t' and t'' in fig. 6(a) because some part of the grains at cap layer are not in contact with neighbor grains. When J_G: 30 erg/cm^2 (J_{ave}: 7.5 erg/cm^2), the *slope* of *M-H* loop becomes infinity as shown in the figure, which means the magnetic grains at cap layer and granular layer are in contact each other. When J_{ave} is varied from 0 to 5 erg/cm^2, at J_{ave} of around 1.0 erg/cm^2 the *slope* starts to increase drastically. When the thickness of cap layer is varied to change the inter-granular coupling, it is calculated that J_{ave}: 1.0 erg/cm^2 can be obtained with cap layer thickness of around 2 nm. This result, agrees quantitatively with experimental result that the slope starts to increase drastically from cap layer thickness of around 2 nm.

4. Conclusions

The quantitative evaluation of inter-granular coupling in the stacked media by analyzing the magnetic domain was shown practicable. According to this method, inter-granular coupling constant of the stacked media when granular layer and cap layer is assumed to be single layer (J_{ave}) can be evaluated with amount of around 2.9 erg/cm^2 which agrees qualitatively with simulation result.

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