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Characterization to realize CoCr-based perpendicular magnetic recording media with high squareness and normalized coercivity

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In an attempt to find a material guidance to realize CoCr-based perpendicular media with high squareness and normalized coercivity, we have performed systematic magnetic characterization to examine the effects of thermal agitation and magnetic exchange interaction. The main results are as follows: (1) With decreasing measuring temperature from R. T. to 4.2 K, normalized coercivity, $H_c/H_k^{\rm grain}$, increases for the medium strongly influenced by thermal agitation, whereas changes slightly for the medium with strong intergranular exchange coupling. (2) All the media characterized in this study have a low value of $H_c/H_k^{\rm grain}$ equal to or less than 0.36 at R. T. (3) An exchange decoupled medium ($\alpha=1.0$) tends to show a large positive $H_n/H_k^{\rm grain}$, which results in a significant decrease of loop squareness S. On the other hand, it is possible to obtain a medium with $S=1$ for $\alpha>1.6$ through the exchange interaction. (4) To realize a medium with $S=1$ and α as small as possible, selection of material with $4\pi M_s/H_k^{\rm grain}=0.2$ (for $\alpha=1.6$) is promising. On the other hand, to realize a medium with $H_c/H_k^{\rm grain}$ as high as possible, selection of material with $4\pi M_s/H_k^{\rm grain}=0.70$ (for $\alpha=1.3$) is favorable.
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I. INTRODUCTION

Much attention has been paid for CoCr-based material to be used for perpendicular magnetic recording media, since it has a uniaxial magnetocrystalline anisotropy $K_u^{\rm grain}$ with condition of $K_u^{\rm grain}>2\pi M_s^2$ so that it has a potential to realize films with perpendicular magnetic anisotropy.[1] An ideal CoCr-based perpendicular magnetic recording media is considered to consist of an assembly of single-domain magnetic grains of the hcp structure with their *c*-axis parallel to the film normal direction. On the assumption that there exists magnetostatic coupling through demagnetizing field and no exchange coupling exists between magnetic grains in a medium, theoretically, the perpendicular magnetic properties should take values such as $H_c/H_k=1$, $S=M_r/M_s=1$, and $\alpha=1$. Here, H_c/H_k is the coercivity H_c normalized by magnetic anisotropy field H_k, S is the hysteresis loop squareness and α is the gradient of hysteresis loop at coercivity, $4\pi(\Delta M/\Delta H)_{\rm H=Hc}$. On the contrary, for experimentally fabricated media, the values of H_c/H_k and S are much smaller than 1, and α is larger than 1. This phenomenon has been discussed for a long time, and is thought to be caused by intergranular exchange coupling,[2,3] magnetic reversal mode,[4,5] thermal agitation[6,7] or initial layer.[8,9] However, to date there are few reports discussing about maximum achievable value of H_c/H_k and suitable material parameters such that a condition $S=1$ and high H_c/H_k can be realized for media fabricated under "conventional process." Here, the conventional process stands for a deposition process at elevated temperature (>150 °C) using dc sputtering and CoCr-based alloy target. In this paper, in an attempt to find a material guidance to realize CoCr-based perpendicular media with high squareness and normalized coercivity, we report a result of systematic magnetic characterization to examine, in particular, the effects of thermal agitation and magnetic exchange interaction.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

$CoCr_{16-24}Pt_{8-20}(B_{0-8},Ta_{0-5})$ thin film media were fabricated by dc magnetron sputtering method on 65 mm diam glass disk substrates using the so-called ultraclean sputtering system.[10] The substrate was heated by quartz lamp and the temperature was varied in the range from 150 to 350 °C. The magnetic film thickness was varied from 5 nm to 200 nm. The underlayer and the protective layer were Ta with the thickness of 25 nm, and C with the thickness of 7 nm, respectively.

M_s, H_c, S, and α, were evaluated by superconducting quantum interference device magnetometer (SQUID, 4.2–400 K), vibrating sample magnetometer (VSM, R. T.), and polar Kerr equipment (PKE, R. T.).

For a medium consisting of a columnar structure and an initial layer, the uniaxial magnetic anisotropy of the columnar structure, $K_u^{\rm grain}$, and the initial layer thickness, $d_{\rm ini}$, were derived by evaluating perpendicular magnetic torque measurement (in the range of 77–400 K) and determined by analyzing $K_{u\perp}^{\rm exp}\times d_{\rm mag}$ vs $d_{\rm mag}$ plot.[11,12] The magnetic anisotropy field of columnar grains, $H_k^{\rm grain}$ was calculated using the relation $H_k^{\rm grain}=2K_u^{\rm grain}/M_s$. Activation volume $V_{\rm act}$, which corresponds with the coherent magnetic reversal volume in a medium, was determined by irreversible susceptibility mea-

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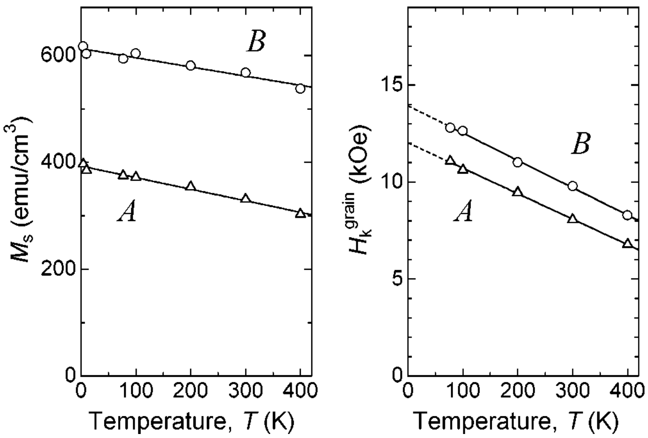

FIG. 1. Saturation magnetization M_s (right) and magnetic anisotropy field H_k^{grain} (left) as a function of measuring temperature, T, for (A) $Co_{64}Cr_{24}Pt_8B_4$ and (B) $Co_{72}Cr_{16}Pt_8B_4$ medium.

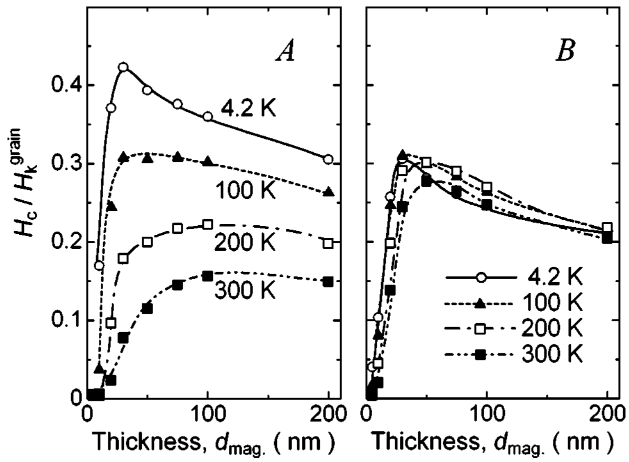

FIG. 2. Normalized coercivity H_c/H_k^{grain} as a function of magnetic film thickness, d_{mag}, for (A) $Co_{64}Cr_{24}Pt_8B_4$ (right) and (B) $Co_{72}Cr_{16}Pt_8B_4$ (left) medium at various measurement temperature.

surement using the following equations:[13] $V_{act} = (kT)/(M_s H_f)$, $H_f = -[dH_r(t)/d\ln(t)]$, where H_f is the fluctuation field, T is the absolute temperature, and k is the Boltzmann's constant. H_f was determined by linear extrapolation of the H_r vs $\ln(t)$ plot.

III. RESULTS AND DISCUSSION

A. Normalized coercivity

First, we will discuss the dominant factors, which decrease H_c/H_k^{grain} by evaluating the magnetic properties at low temperature for perpendicular media using CoCrPtB magnetic layer.

Figure 1 shows dependence of M_s and H_k^{grain} on measurement temperature, T for (A) $Co_{64}Cr_{24}Pt_8B_4$ and (B) $Co_{72}Cr_{16}Pt_8B_4$ media. Both media have very thin initial layer with the thickness of 2.6 nm for the medium (A) and 1.9 nm for the medium (B), respectively.[14] It is found that M_s (in the range of 4.2–400 K) and H_k^{grain} (in the range of 77–400 K) varies linearly with T. Therefore, we believe that it is reasonable to determine H_k^{grain} at the temperature lower than 77 K by extrapolating the linear portion of H_k^{grain} vs T plot to $T \rightarrow 0$ K.

Figure 2 shows H_c/H_k^{grain} as a function of magnetic film thickness, d_{mag}, for (A) $Co_{64}Cr_{24}Pt_8B_4$ and (B) $Co_{72}Cr_{16}Pt_8B_4$ medium measured at various temperature. For the media (A) measured at 300 K, H_c/H_k^{grain} increases with increasing d_{mag} and saturates at the value of 0.15 for $d_{mag} > 100$ nm. With decreasing measurement temperature, the magnitude of H_c/H_k^{grain} increases and H_c/H_k^{grain} gradually takes maximum against d_{mag}. It is found that the maximum value of H_c/H_k^{grain} at 4.2 K is 0.44 at $d_{mag} = 30$ nm. In the case of the medium (B), H_c/H_k^{grain} has already taken a maximum value against d_{mag} even at 300 K, and H_c/H_k^{grain} vs d_{mag} shows slight dependence on measurement temperature. The maximum value of H_c/H_k^{grain} at 4.2 K is 0.31 at $d_{mag} = 30$ nm. The decrease of H_c/H_k^{grain} for the media with thick magnetic layer thickness ($d_{mag} \geqslant 30$ nm) is considered to be caused by incoherent magnetization reversal.[15] In this study, the discussion will be focused on the properties for a medium with thin magnetic layer thickness ($d_{mag} \leqslant 30$ nm). Comparing the media (A) with (B), H_c/H_k^{grain} for the medium (A) is more sensitive to measurement temperature, which means thermal agitation strongly affects the magnetization reversal of the medium. On the other hand, although the thermal stability of magnetization for the medium (B) is higher, the maximum value of H_c/H_k^{grain} is comparatively low. This is considered to be caused by strong exchange interaction between the columnar grains in the medium (B). Note that, for CoCr-based media with thin initial layer and with coherent magnetization reversal, H_c/H_k^{grain} at room temperature is strongly affected by both of the thermal agitation and the exchange coupling.

In Fig. 3, H_c/H_k^{grain} for 30 nm thick CoCrPtB (open circle), CoCrPtTa (solid gray triangle), and CoCrPt (solid square) media with various compositions measured at R. T. is plotted against thermal stability factor, $K_u^{grain}V_{act}/kT$. In this plot, the media with thin initial layer ($d_{ini} < 3$ nm), and with high H_c, obtained by optimizing substrate temperature, were used. The values of $K_u^{grain}V_{act}/kT$ are dispersed in the range of 68 to 300. It is found that H_c/H_k^{grain} plotted against $K_u^{grain}V_{act}/kT$ forms a convex region shown by the gray area. Dispersed region of H_c/H_k^{grain} takes a fairly low maximum of 0.36 at $K_u^{grain}V_{act}/kT = 150$. To consider the effect of exchange interaction, in Fig. 3, equivalue curves of α ($\alpha = 1.0$, 1.2, 1.4, and 1.6) are drawn. It is found that along the equivalue curves of α, H_c/H_k^{grain} monotonously increases with increasing $K_u^{grain}V_{act}/kT$, and with decreasing α the gradient of the equivalue curve drastically increases. Taking these trends into consideration, the equivalue curve of $\alpha = 1$ can be easily presumed and is shown by the broken line. It is clarified that along the equivalue curve of $\alpha = 1$, H_c/H_k^{grain} linearly increases with increasing $K_u^{grain}V_{act}/kT$. This means that if intergranular exchange coupling is negligible, H_c/H_k^{grain} should take high value with the improvement of the thermal stability factor (e.g., $H_c/H_k^{grain} = 0.5$ at $K_u^{grain}V_{act}/kT = 70$: $\alpha = 1$). It is concluded that the low maximum of H_c/H_k^{grain} of the current media prepared with conventional process is considered to be dominated by the ef-

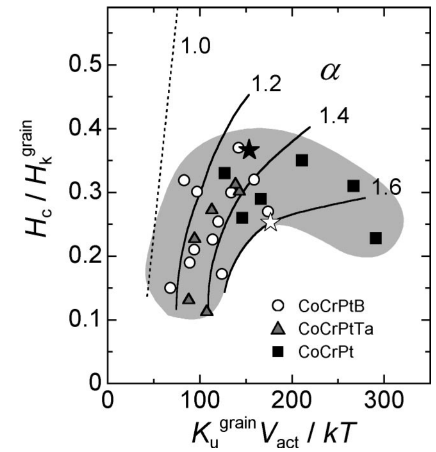

FIG. 3. Normalized coercivity H_c/H_k^{grain} plotted against $K_u^{\mathrm{grain}}V_{\mathrm{act}}/kT$ for 30 nm thick CoCrPtB (open circle), CoCrPtTa (solid gray triangle), and CoCrPt (solid square) media with various compositions measured at room temperature. (☆) and (★) correspond to the media with $S=1$ (α as low as possible), and H_c/H_k^{grain} as high as possible, respectively.

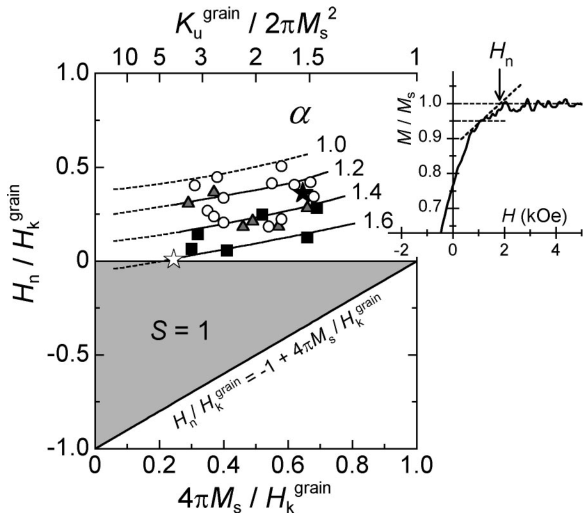

FIG. 4. Normalized nucleation field H_n/H_k^{grain} plotted against $4\pi M_s/H_k^{\mathrm{grain}}$ for 30 nm thick CoCrPtB (open circle), CoCrPtTa (solid gray triangle), and CoCrPt (solid square) media with various compositions measured at room temperature. The supplementary graph shows the determination method of H_n. (☆) and (★) correspond to the media with $S=1$ (α as low as possible), and H_c/H_k^{grain} as high as possible, respectively.

fects of thermal agitation for $K_u^{\mathrm{grain}}V_{\mathrm{act}}/kT<150$, and intergranular exchange coupling for $K_u^{\mathrm{grain}}V_{\mathrm{act}}/kT>150$.

B. Loop squareness

To obtain a guideline of realizing a medium with $S=1$, in Fig. 4, nucleation field H_n normalized by H_k^{grain}, H_n/H_k^{grain}, for 30 nm thick CoCrPtB (open circle), CoCrPtTa (solid gray triangle), and CoCrPt (solid square) media with various compositions was plotted against $4\pi M_s/H_k^{\mathrm{grain}}$. Note that to realize $S=1$, the sign of H_n must be negative. All the magnetic properties were evaluated at R. T. H_n of each medium was determined by taking the intersection of $M=M_s$ line with the tangential line at $M=0.95$ M_s in hysteresis loop (refer to the supplementary graph in Fig. 4). For comparison, the properties for ideal perpendicular media are shown by the thick line which satisfies the relation of $H_n/H_k^{\mathrm{grain}}=-1+4\pi M_s/H_k^{\mathrm{grain}}$ for $4\pi M_s/H_k^{\mathrm{grain}}<1$. Therefore, to realize a medium with $S=1$, the magnetic properties should satisfy the condition shown as the gray zone. In the present study, the values of $4\pi M_s/H_k^{\mathrm{grain}}$ are dispersed in the range from 0.29 to 0.69. It is found that the values of H_n/H_k^{grain} plotted against $4\pi M_s/H_k^{\mathrm{grain}}$ show positive sign, which means all the evaluated media has $S<1$. To estimate the effect of exchange interaction, in Fig. 4, equivalue curves of α ($\alpha=1.0$, 1.2, 1.4, and 1.6) are also drawn. It is found that along the equivalue curves of α, H_n/H_k^{grain} monotonously decreases with decreasing $4\pi M_s/H_k^{\mathrm{grain}}$, and with increasing α from 1.0 to 1.6, the equivalue curves gets close to the gray area. These results reveal that for the current media, (1) exchange decoupled medium ($\alpha=1.0$) tends to show a large positive H_n/H_k^{grain}, which results in a significant decrease of S, (2) it is possible to obtain a medium with $S=1$ for $\alpha>1.6$ through the exchange interaction.

C. Guiding principle for high-S and H_c/H_k^{grain}

From the above discussion, the problem for current media has been clarified, that is fairly low S and H_c/H_k^{grain} due to thermal instability or strong exchange interaction. Considering these facts, a guiding principle of material for CoCr-based perpendicular media, fabricated under conventional process, with $S=1$ and high H_c/H_k^{grain} is discussed. In general, the exchange interaction between magnetic grains of a medium should be suppressed to obtain low transition noise. Therefore, to realize a medium with $S=1$ and α as low as possible, selection of material with $4\pi M_s/H_k^{\mathrm{grain}}=0.25$ is promising. If this material is applied, the media is predicted to show $K_u^{\mathrm{grain}}V_{\mathrm{act}}/kT=180$ and $H_c/H_k^{\mathrm{grain}}=0.25$ ($\alpha=1.6$; (☆) in Figs. 3 and 4). On the other hand, to realize a medium with H_c/H_k^{grain} as high as possible, selection of material with $4\pi M_s/H_k^{\mathrm{grain}}=0.70$ is favorable. In this case, the media is predicted to show $K_u^{\mathrm{grain}}V_{\mathrm{act}}/kT=150$ and $H_c/H_k^{\mathrm{grain}}=0.36$ ($\alpha=1.3$; (★) in Figs. 3 and 4).

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