Evaluation of interlayer ferromagnetic coupling for stacked media by adding reference layer

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Abstract. The trial for quantitative evaluation of interlayer ferromagnetic coupling between granular and cap layer in stacked media is reported. The evaluation is realized by analyzing M-H loop of stacked media with another reference layer added on the cap layer. The reference layer is antiferromagnetically coupled with the cap layer through non-magnetic spacer layer. In this experiment, Rh which leads to antiferromagnetic coupling constant along film normal direction of around 2 erg/cm² was used as non-magnetic spacer layer. According to the evaluation result done by this method, when thickness of the spacer Pd layer between granular layer and cap layer is increased to 1.1 nm, ferromagnetic coupling constant is weakened to 7.2 erg/cm² which results in reduction of saturation field.

1. Introduction
The stacked media has been widely used for high density perpendicular recording media [1], [2]. The media consists of a-CoCrPt-oxide granular layer and a cap layer with continuous structure. In this media, the control of intergranular coupling through the cap layer is very important to reduce the saturation field which results in improvement of the writing ability [3]. Excessive intergranular coupling will increase the magnetic cluster size which limits the recording density.

Exchange spring media with spacer layer inserted in between granular layer and cap layer has been widely studied in order to further control the intergranular coupling [4]. In such as media, the weakened interlayer ferromagnetic coupling between granular layer and cap layer can suppress the increase of intergranular coupling in granular layer without sacrificing writing ability which results in smaller magnetic clusters. Therefore quantification of interlayer ferromagnetic coupling between granular layer and cap layer is indispensable. However, currently there is no detail report regarding the qualitative evaluation of the interlayer ferromagnetic coupling constant.

In this paper, we report the trial for quantitative evaluation of interlayer ferromagnetic coupling between granular and cap layer in stacked media. We also show the correlation between interlayer ferromagnetic coupling and saturation field.

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2. Experimental procedure

All layers were fabricated on glass substrate at room temperature with DC magnetron sputtering system. The stacking structure of the samples for interlayer ferromagnetic coupling evaluation:

Glass/Ta(5 nm)/Pt(6 nm)/Ru(20 nm)/Granular layer/Pd spacer layer/Cap layer/ Rh/ Reference layer. Co$_{74}$Cr$_{10}$Pt$_{16}$-SiO$_2$ (8 mol%) (16 nm) with $M_s$ value of around 640 emu/cm$^3$ and grain size of around 10 nm was used as granular layer. [Co(0.6 nm)/Pd(1.1 nm)]$_n$ multilayer with $n=3$ and $n=5$ were used for cap layer and reference layer. $M_s$ value of the cap layer and reference layer were around 580 emu/cm$^3$.

For evaluation of saturation field ($H_s$), stack media without reference layer were also prepared. The thickness of Pd spacer layer (s-Pd) is varied from 0 to 3.1 nm to change the strength of ferromagnetic coupling (F-coupling) between granular layer and cap layer. Reference layer was deposited above Rhodium to generate antiferromagnetic coupling (AF-coupling) between cap layer and reference layer.

The samples for evaluation of interlayer ferromagnetic coupling were prepared with Rhodium thickness of 0.8, 0.9 and 1.1 nm. During the experiment for finding non-magnetic spacer layer which leads to larger AF-coupling, s-Pd thickness was fixed at 3.1 nm to avoid the effect of F-coupling. The exchange coupling field ($H_{ex}$) of AF-coupling was determined from minor $M$-$H$ loop measured by VSM. $H_{ex}$ value is defined as the distance from centre of the minor $M$-$H$ loop to $H=0$ axis.

3. Result and discussion

3.1. Evaluation of ferromagnetic coupling with reference layer

3.1.1. Evaluation method

Figure 1 shows the schematic $M$-$H$ loop for stacked media with and without reference layer. (a) $M$-$H$ loop for stacked media without reference layer. (b) $M$-$H$ loop for stacked media with reference layer when F-coupling is larger than AF-coupling. (c) $M$-$H$ loop for stacked media with reference layer when F-coupling is smaller than AF-coupling. The arrows at $M$-$H$ loop of figure 1(a) show the magnetization of cap layer and granular layer from the top. The arrows at $M$-$H$ loop of figure 1(b) and 1(c) show the magnetization of reference layer, cap layer and granular layer respectively from the top. The interlayer F-coupling constant ($J_F$) between granular layer and cap layer was quantified by observing whether the cap layer is coupled with granular or reference layers during magnetization reversal. When F-coupling is larger than AF-coupling, magnetization reversal of cap layer is mainly affected by F-coupling. On the contrary, when F-coupling is smaller than AF-coupling, both AF-coupling and F-coupling influenced magnetization reversal of cap layer.

Figure 1. The schematic $M$-$H$ loop for stacked media with and without reference layer. (a) $M$-$H$ loop for stacked media without reference layer. (b) $M$-$H$ loop for stacked media with reference layer when F-coupling is larger than AF-coupling. (c) $M$-$H$ loop for stacked media with reference layer when F-coupling is smaller than AF-coupling.
3.1.2. Finding spacer layer material for larger anti ferromagnetic coupling

In order to quantify the large F-coupling, we search for the non-magnetic spacer layer material which has larger AF-coupling. We tried Rh as the spacer layer which was reported to have very large AF-coupling along in-plane direction between Co layers [5].

Figure 2 shows the dependence of AF-coupling constant ($J_{AF}$) along film normal direction on Rh and Ru thickness. We found that $J_{AF}$ shows the peak at Rh thickness of 0.9 nm with value of 1.95 erg/cm² which is around twice as compared to Ru. In this experiment, we prepared samples with Rh thickness of 0.8, 0.9 and 1.1 nm to vary the strength of AF-coupling.

![Figure 2](image.png)

**Figure 2.** The dependence of AF-coupling constant ($J_{AF}$) along film normal direction on Rh and Ru thickness.

3.1.3. Evaluation of ferromagnetic coupling

Figure 3 shows the dependence of $J_F$ and $J_{AF}$ on s-Pd layer thickness at Rh thickness of around 0.9 nm. The thickness of s-Pd was changed from 0 to 3.1 nm to vary the F-coupling. Arrows at the $M$-$H$ loop shows the magnetization at reference layer, cap layer and granular layer from the top. For s-Pd thickness less than 2.1 nm $J_F$ is larger than $J_{AF}$ that magnetization at cap layer is fixed by F-coupling and magnetization at reference layer is reversed by AF-coupling. $J_{AF}$ can be determined with following equation.

$$J_{AF} = M_s^{ref} t^{ref} H_{ex}$$  (1)

$M_s^{ref}$: Saturation magnetization of reference layer, $t^{ref}$: thickness of reference layer.

When s-Pd thickness is thicker than 2.2 nm, $J_F$ becomes large enough that magnetization reversal at cap layer is influenced by AF-coupling and F-coupling. Therefore the exchange coupling constant becomes the combination of $J_{AF}$ and $J_F$ which can be determined with following equation.

$$J_{AF} + J_F = M_s^{cap} t^{cap} H_{ex}$$  (2)

$M_s^{cap}$: Saturation magnetization of cap layer, $t^{cap}$: thickness of cap layer.

From this result $J_F$ for s-Pd thicker than 2.2 nm can be calculated by equation (1) and (2). The same experiment was conducted also for Rh thickness 0.8 nm and 1.1 nm.

Figure 4 shows the dependence of $J_F$ on s-Pd thickness at various Rh thicknesses. When s-Pd thickness is 0 nm, $J_F=100$ erg/cm² is plotted [6]. Concerning exponential decay of $J_F$ against s-Pd thickness [7], $J_F$ can be estimated as the magnitude of around 7.2 erg/cm² for cap-media with typical s-Pd thickness of 1.1 nm.
3.2. Magnetic properties of stacked media

Figure 5 shows the $M-H$ loop of stacked media with various s-Pd thickness. When the thickness of s-Pd is increased to 1.1 nm, slightly decrease of $H_s$ can be observed from the $M-H$ loop. Further increase of the s-Pd thickness will increase the $H_s$. At s-Pd thickness of around 2.3 nm, a kink can be observed at around zero field which means magnetization reversal for granular layer and cap layer starts to happen separately.

Figure 6 shows the dependence of $H_s$ on $J_F$ and s-Pd thickness. When 1.1 nm of s-Pd is inserted $J_F$ decreases from 100 erg/cm$^2$ to 7.2 erg/cm$^2$ which results in the reduction of $H_s$ from 7.2 kOe to 6.8 kOe. The tendency of $H_s$ reduction by inserting spacer layer agrees with previous report [8]. Further decrease of $J_F$ will increase $H_s$ of the media. From this result, by inserting s-Pd thickness 1.1 nm, interlayer ferromagnetic coupling is reduced that decreases $H_s$. 

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**Figure 3.** The dependence of $J_F$ and $J_{AF}$ on s-Pd layer thickness at Rh thickness of 0.9 nm.

**Figure 4.** The dependence of $J_F$ on s-Pd thickness at various Rh thicknesses.
Figure 5. M-H loop of stacked media with various s-Pd thicknesses. (a) s-Pd: 0 nm, (b) s-Pd: 1.1 nm, (c) s-Pd: 1.9 nm, (d) s-Pd: 2.3 nm.

Figure 6. $H_s$ dependence on $J_F$ and s-Pd thickness.

4. Conclusions
The qualitative evaluation of interlayer exchange coupling between granular and cap layer by adding another reference layer was shown practicable. According to this method $J_F$ between granular layer and cap layer can be evaluated by analyzing $M$-$H$ loop. At s-Pd layer thickness of around 1.1 nm $J_F$ is decreased from 100 erg/cm$^2$ to 7.2 erg/cm$^2$ which results in $H_s$ reduction of around 0.4 kOe.

5. References
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