Effect of Rh spacer on Synthetic-Antiferromagnetic Coupling in FeCoB/Rh/FeCoB Films

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Abstract. Effect of Rh spacer on synthetic antiferromagnetic (SAF) coupling was investigated in subnano-crystalline (Fe_{65}Co_{35})_{88}B_{12} (30 nm)/ Rh/ (Fe_{65}Co_{35})_{88}B_{12} (30 nm) films. The flopping field ($H_f$) showed oscillatory behavior with respect to Rh thickness, $d_{Rh}$. The 1st peak of $H_f$ appeared at $d_{Rh} = 0.9$ nm, and the 2nd at $d_{Rh} = 1.7$ nm. These results are analyzed in terms of interlayer coupling effect including the bilinear ($J_1$) and biquadratic ($J_2$) coupling energy, and found to be 0.65 erg/cm$^2$ for $J_1$ and 0.12 erg/cm$^2$ for $J_2$ at the 1st peak. Compared to SAF coupling with Ru spacer, the 1st peak thickness with Rh spacer is thicker. This is because the effective spacer layer thickness decreases by the polarization of Rh neighboring FeCo based material.

1. Introduction
For high density perpendicular recording media, a thick soft magnetic underlayer (SUL) is required for the magnetic flux path for writing. The thick SUL introduces spike noise and wide adjacent track erasure (WATE). To avoid these problems, the SUL with synthetic antiferromagnetic (SAF) coupled structure have been widely used [1-3] as following reasons [4]; 1) Néel walls are formed in the top and bottom soft magnetic (SM) layers in a pair [5], which is effective for suppression of spike noise, and 2) Low susceptibility are realized when the angle of applied field is slightly tilted from the film normal, which can efficiently restrain WATE. We have already reported that large flopping field ($H_f$) appeared for (Fe_{65}Co_{35})_{88}B_{12} (30 nm)/ Ru/ (Fe_{65}Co_{35})_{88}B_{12} (30 nm) stacked SUL at the 1st peak with Ru spacer thickness ($d_{Ru}$) of 0.3 nm due to the extremely large unidirectional interlayer coupling energy $J_1$ of 1.9 erg/cm$^2$ as a result of composition dependence of SM materials [6-7]. In this paper, we investigate interlayer coupling by using Rh as a spacer material to obtain the material guide of spacer for further enhancement of $H_f$.

2. Experimental Procedure
All samples were fabricated by the dc magnetron sputtering method at room temperature under an Ar gas pressure of 0.6 Pa. The stacking structure of the samples was glass sub./ (Fe_{65}Co_{35})_{88}B_{12} (30 nm)/ Rh ($d_{Rh}$ nm)/ (Fe_{65}Co_{35})_{88}B_{12} (30 nm). Ru was also chosen as a spacer material for reference. The (Fe_{65}Co_{35})_{88}B_{12}, Rh and Ru layers were sputtered with deposition rate of 2.38, 0.26 and 0.15 nm/s, respectively. For confirmation of polarization of Rh and Ru, Co_{100-x}Rh$_x$ and Co$_{100-x}$Ru$_x$ films were also deposited by cosputtering with Co and Rh or Ru by varying the discharge power for each target. Magnetic properties of the samples were evaluated by vibrating sample magnetometer.

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3. Results and Discussion

Figure 1 show $M-H$ loops along the easy magnetization direction for FeCoB/ Rh ($d_{Rh}$ nm)/ FeCoB films where $d_{Rh}$ is (a) 0.9 nm, and (b) 1.7 nm. As seen in Figures 1(a) and (b), both samples show a small hysteresis in their $M-H$ loop, which suggests that the FeCoB in these samples become soft magnetic. In the magnetization process for a stacked film with SAF interlayer coupling, the magnetization is almost cancelled out near zero field, as shown for both samples, i.e. the magnetic moments of the top and bottom SM layers are antiparallelly aligned. As the external field increases, the magnetization flops at 25 Oe for (b) and 60 Oe for (a). Increasing the external field further brings the magnetic moments to saturation through a rotation-magnetized process. Figure 2 shows a change in $H_f$ for samples using Rh spacer (solid circle) as a function of spacer thickness. For comparison, change in $H_f$ using Ru spacer (open triangle) is also shown in the figure. With decreasing $d_{Rh}$, $H_f$ oscillates and takes the local maximum at $d_{Rh} = 2.2, 1.7, \text{ and } 0.9 \text{ nm}$. Each peak is indicated as the 3rd, 2nd, and 1st peak with $d_{Rh}$. At the 1st peak, $H_f$ shows 60 Oe for the maximum value. In case of Ru spacer, $H_f$ increases, attaining the local maxima at $d_{Ru} = 3.3, 1.9, 0.9, \text{ and } 0.3 \text{ nm}$. Each peak is indexed as the 4th, 3rd, 2nd, and 1st peak with $d_{Ru}$ as well as the case of Rh spacer. It should be noted that SAF coupling does not appear when $d_{Rh} < 0.9 \text{ nm}$ even using the same SM layer material as Ru spacer.

![Figure 1](image_url1)

**Figure 1.** $M-H$ loops along the easy magnetization direction for a FeCoB (30 nm)/ Rh ($d_{Rh}$ nm)/ FeCoB (30 nm) samples where $d_{Rh}$ is (a) 0.9 nm, (b) 1.7 nm. The figures at the left show a wide $H$ range; the ones at the right are expansions around the flop field. Solid and dashed lines are experimental and calculated data, respectively.

![Figure 2](image_url2)

**Figure 2.** Change in $H_f$ for samples with SAF structure using (solid circle) Rh and (open triangle) Ru spacers as a function of spacer layer thickness.
The mechanism of enhancement of the $H_f$ at the 1st peak in FeCoB/ spacer/ FeCoB films is phenomenologically analyzed in terms of interlayer coupling effect. The total magnetic energy per unit area ($E_T$) including bilinear coupling energy, $J_1\cos(\phi_1 - \phi_2)$, and biquadratic coupling energy, $J_2\cos^2(\phi_1 - \phi_2)$, in SAF structure is expressed as follows [8];

$$E_T = K_u d_{SM}(\sin^2 \phi_1 + \sin^2 \phi_2) + J_1\cos(\phi_1 - \phi_2) + J_2\cos^2(\phi_1 - \phi_2) - M_s H_{SM}(\cos \phi_1 + \cos \phi_2).$$  \hspace{1cm} (1)

The $d_{SM}$ and $K_u$ denote the thickness and uniaxial magnetic anisotropy energy of SM layer, respectively. And $\phi_1$ and $\phi_2$ are the angles between easy magnetization direction and magnetic moment of top and bottom SM layers. Note that in this equation, domain structure and dispersion of magnetic anisotropy are not considered. The net magnetization of the two SM layers is calculated by the equilibrium angle of $\phi_1$ and $\phi_2$, which were determined from the minimum energy condition of equation (1). Then $M$--$H$ loop is derived using following equation;

$$M = M_s(\cos \phi_1 + \cos \phi_2).$$ \hspace{1cm} (2)

The values of $J_1$ and $J_2$ for FeCoB/ Rh/ FeCoB films were evaluated from the best fitting of measured $M$--$H$ loop to that calculated by equation (1) [5]. In fitting, correspondence of $M$--$H$ loops until a half of rotation reversal region was considered because higher-order terms were ignored (see figure 3). The values of $K_u$ and $M_s$ used in the calculation were experimentally determined on $1.5 \times 10^4$ erg/cm$^3$, 1450 emu/cm$^3$, respectively.

![Figure 3](image-url) A typical result of fitting for $M$-$H$ loop. Solid and broken lines correspond to experimental and calculated results, respectively, for the sample with $d_{Rh} = 0.9$ (nm).

Figures 4(a) and (b) show evaluated $J_1$ and $J_2$ against spacer thickness, respectively. $J_1$ and $J_2$ take the local maximum on the same $d_{Rh}$ where $H_f$ takes peaks. Now, discussion is focused on the 1st peak. At the 1st peak of $H_f$, concerning that $J_1$ and $J_2$ are one or two figures larger than $K_u d_{SM}$ and that $J_1$ is larger than $2J_2$ (see figure 4(a) and (b)), $H_f$ can be expressed as follows;

$$H_f = \frac{2}{M_s d_{SM}}\sqrt{K_u d_{SM}(J_1 - 2J_2 - K_u d_{SM})} \approx \frac{2}{M_s d_{SM}}\sqrt{K_u d_{SM}(J_1 - 2J_2)}.$$ \hspace{1cm} (3)

According to equation (3), $H_f$ has linear relationship with $\sqrt{J_1 - 2J_2}$. As shown in figure 4(a) and 4(c), in the present films, $J_1 - 2J_2$ takes the maximum at the same $d_{Rh}$ as $J_1$. Therefore, the enhancement of $H_f$ of the 1st peak is mainly originated from the enhancement of $J_1$. This result is similar to the stacked SUL with Ru spacer on our previous report [6]. FeCoB/ Rh / FeCoB film exhibits larger 1st peak
thickness of Rh and less interlayer coupling strength in comparison with the film with Ru spacer; this result is in good agreement with Co/Rh and Co/Ru multilayers [9]. In [9], it is shown that in the case of multilayer the indirect exchange-coupling strength increases from the 5d to 4d to 3d transition metals and increases exponentially with the number of $d$ electrons along each period; it is also pointed out that the intermixing or the local interaction between the magnetic and spacer-layer atoms is one possible reason for the different spacer-layer thickness corresponding to the 1st peak. Here, the polarization of Rh neighboring ferromagnetic atoms is considered to be the most possible reason for the thicker Rh than Ru at the 1st peak and is evaluated as follows.

In order to consider the large thickness of the 1st peak of Rh spacer, polarization of Rh neighboring ferromagnetic atoms were evaluated by using glass Sub./NiFeCr (20 nm)/ Ru (20 nm)/ CoRh (20 nm)/ C (7 nm) films were fabricated. Figure 5 shows the magnetization per 1 Co atom $m_{\text{Co}}$ for Co$_{100-x}$Rh$_x$ alloy films as a function of Rh content, $x$. $m_{\text{Co}}$ for Co$_{100-x}$Ru$_x$ alloy films with the same underlayer is also shown. $m_{\text{Co}}$ is evaluated by assuming that the whole magnetization of the film comes from Co atoms in the film. A Co film has $m_{\text{Co}}$ of 1.5–1.6 $\mu_B$/atom, which is smaller than reported value of 1.7 $\mu_B$/atom [10]. This may be because slight carbonization and/or oxidization after deposition [11]. $m_{\text{Co}}$ monotonically decreases with increasing Ru content for CoRu films, whereas increment of $m_{\text{Co}}$ was observed with Rh content up to 20 at.%. Here, 20 at.% corresponds to the existence of at least 1 Rh atom in neighbors of Co. Applying this result to the case of FeCoB/ Rh/ FeCoB films with SAF coupling, the effective Rh layer thickness decreases, since the monolayers of top and bottom surface of Rh are polarized (see figure 6).

In summary, the intrinsic strong $J_1$ was realized in FeCoB/ Rh/ FeCoB system similar to that using Ru spacer. On the other hand, the 1st peak thickness of $H_f$ using Rh is 0.9 nm, which is thicker than that for sample with Ru spacer. The decrease of effective spacer thickness due to polarization is the most possible reason.

![Figure 4](image1.png)  
**Figure 4.** The variation of (a) $J_1$, (b) $J_2$, and (c) $J_1-2J_2$ for samples with SAF structure using (solid circle) Rh and (open triangle) Ru spacers as a function of spacer layer thickness.

![Figure 5](image2.png)  
**Figure 5.** Dependence of moment per Co atom $m_{\text{Co}}$ for Co$_{100-x}$Rh$_x$ and Co$_{100-x}$Ru$_x$ films on Rh or Ru content $x$. 

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