Interlayer exchange coupling in perpendicularly magnetized synthetic ferrimagnet structure using CoCrPt and CoFeB

D. Watanabe1, S. Mizukami1, F. Wu1, M. Oogane2, H. Naganuma2, Y. Ando2, and T. Miyazaki1
1WPI-AIMR, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan
2Graduate School of Engineering, Tohoku University, Aoba-yama 6-6-05, Sendai 980-8579, Japan
E-mail: watanabe@wpi-aimr.tohoku.ac.jp

Abstract. Interlayer exchange coupling in synthetic ferrimagnet structures consisting of perpendicularly magnetized CoCrPt and in-plane magnetized CoFeB layers, which are coupled by a Ru thin spacer, were investigated. The magnetization of the CoFeB layer turned perpendicular to the film plane after annealing at 300°C because of the appearance of interlayer coupling from the CoCrPt layer. The coupling varied between antiferromagnetic and ferromagnetic depending on the Ru spacer thickness. The sign and strength of the coupling were also observed through analyses of magnetization curves and ferromagnetic resonance spectra.

1. Introduction
Perpendicularly magnetized films with a large magnetic anisotropy have been desired for electrodes of magnetic tunnel junctions (MTJs) to maintain a thermal stability in a high-density magnetoresistive random access memory (MRAM) using spin torque switching. In recent years, relatively-low switching current density was reported in MgO-based MTJs with a perpendicular magnetic anisotropy (PMA) having a sufficient thermal stability for reliable devices [1]. However, their output voltages were smaller than those of in-plane magnetized MTJs [2]. To improve the output voltages, the insertion of a high-spin-polarized CoFeB at the interface between PMA-electrode and MgO barrier is unavoidable. Therefore, perpendicularly magnetized synthetic ferrimagnet (SyF) structures consisting of PMA/Ru/CoFe(B) were investigated in this study [3]. It is expected that the PMA material in this structure provides a high magnetic anisotropy (thermal stability) to the CoFeB layer because of the interlayer exchange coupling through the Ru spacer. Moreover, the reduction of an effective volume of magnetic free layer has an advantage for a low switching current. In this paper, to confirm an applicability of perpendicularly magnetized SyF structures to the MTJs, we investigated their coupling strength as an important factor to keep CoFeB magnetization perpendicular to the film plane.

As described herein, we prepared SyF structure having CoCrPt films as a PMA material and in-plane magnetized CoFeB and investigated their mutual interlayer exchange coupling using magnetization curves and ferromagnetic resonance (FMR) technique. Actually, CoCrPt presents some advantages for mass production process including easy growth with hcp c-axis orientation required to
high PMA at low substrate temperature ($T_s$). Additionally, CoCrPt has low saturation magnetization ($M_s$), which is required theoretically for a low critical current density in spin transfer switching.

2. Experimental procedure

Using an ultra high vacuum sputtering system, samples of substrate/Ta(5 nm)/Ru(10 nm)/CoCrPt(4 nm)/Ru($t_{Ru}$)/CoFeB($t_{CoFeB}$)/MgO(2.5 nm)/Ta(10 nm) were deposited on a thermally oxidized Si wafer. Here, $t_{Ru}$ and $t_{CoFeB}$ respectively signify the Ru spacer and CoFeB layer thickness. The CoCrPt films were grown on c-axis oriented Ru buffer layer using a Co$_{65}$Cr$_{15}$Pt$_{20}$ sputtering target with heating of the substrate at $T_s$. The MgO layers on the CoFeB were prepared to resemble actual tunnel magnetoresistance junctions so that the CoFeB will crystallize to (100)-textured orientation following MgO after annealing. Magnetic properties such as saturation magnetization and coercive field were characterized respectively using a vibrating sample magnetometer (VSM) and superconducting quantum interference device (SQUID) with maximum applied field of 15 and 50 kOe. The FMR spectra of the CoFeB films were measured using sweeping magnetic field perpendicular to the film plane using X-band (9.77 GHz) and TE$_{102}$ cavity at room temperature.

3. Results and Discussion

The CoCrPt films with thickness of 2-10 nm exhibited hcp c-axis orientation at $T_s = 250^\circ$C, as identified using X-ray diffraction. Magnetization measurement showed that the CoCrPt films have a perpendicular anisotropy with an effective anisotropy field of 6-8 kOe and low $M_s$ of 360 emu/cm$^3$. The 4-nm-thick CoCrPt has larger coercive field, $H_c = 670$ Oe and closer nucleation field to $H_c$ than that of the other samples. The surface of the sputtered CoCrPt is quite flat; surface roughness of 0.14 nm was found using atomic force microscopy, so that a thin Ru spacer can be deposited as a continuous layer on the CoCrPt film.

![Figure 1](image-url)

**Figure 1.** Magnetization curves of the SyF structure of CoCrPt(4 nm)/Ru(0.6 nm)/CoFeB (1 nm) measured using VSM at RT (a) before and (b) after annealing at 300$^\circ$C ((c) shows their full loops). Solid and broken lines respectively correspond to the measurements with applying fields perpendicular and in the in-plane direction.

Figure 1 shows the in-plane and perpendicular magnetization curves of the SyF structure with $t_{Ru} = 0.6$ nm and $t_{CoFeB} = 1$ nm before (Fig. 1(a)) and after (Fig. 1(b)) annealing at 300$^\circ$C. The curves of the as-prepared sample in Fig. 1(a) imply the presence of both perpendicular and in-plane anisotropy, respectively derived from CoCrPt and amorphous CoFeB, respectively. After annealing at 300$^\circ$C, as magnetization curves presented in Fig. 1(b), the remnant magnetization of the in-plane direction disappeared, although that of the perpendicular direction decreased, indicating that magnetization of the CoFeB layer pointed perpendicular and opposite to the CoCrPt magnetization direction. Such transformation of magnetization curves was attributed to antiferromagnetic interlayer coupling between PMA-CoCrPt and CoFeB. It noteworthy that the coercive field became larger than that of
single CoCrPt films. Figure 1(c) shows a full range of magnetization loops displayed in Fig. 1(b). Both magnetization of two ferromagnets switch at $H_c$ and then gradually tilt toward perpendicular direction until saturation field, $H_s$, defined in Fig. 1(c).

Figure 2(a) shows the coercive fields in the SyF structures as a function of the Ru spacer thickness as measured by VSM. Only the sample with $t_{Ru} = 0.4$ nm was measured using a SQUID magnetometer because its $H_s$ of 16 kOe was too large to measure using VSM. The broken line in Fig. 2(a) shows the $H_c$ of the single CoCrPt film described above. The $H_s$ of $t_{Ru} = 0.6$ and 0.8 nm become larger than that of intrinsic CoCrPt films, indicating that the thermal stability as the memory layer of the devices also increases. The exchange coupling energy, $J_{ex}$ between the CoCrPt and CoFeB layers was calculated using $J_{ex} = -(H_s/2) \cdot M_{s1}t_1 \cdot M_{s2}t_2 / (M_{s1}t_1 + M_{s2}t_2)$ [4], where $M_{s1,2}$ and $t_{1,2}$ respectively represent the saturation magnetization and the CoCrPt (CoFeB) layer thickness. The $M_{s2}$ of 900 emu/cm$^3$ was estimated from magnetization curves of Fig. 1(c). The $J_{ex}$ varied by the Ru spacer thickness as presented in Fig. 2(b) and ferromagnetic coupling was observed at $d_{Ru} = 1.2$ nm. Consequently, it seems that the Ru thickness dependence of $J_{ex}$ indicates a part of oscillatory behavior, as generally observed in interlayer coupling systems, in which both two ferromagnets have in-plane or perpendicular anisotropy [5,6]. The order of the coupling energy is comparable to the reported values for in-plane SyF structures of CoFeB/Ru/CoFeB [7].

To improve the output voltage of the MTJs, the CoFeB layer thickness near the MgO barrier should be about at least 2 nm. However, when the CoFeB of our perpendicular SyF structures thickened to more than 1 nm, the magnetization of the CoFeB layer tilted to the in-plane direction. Thus, it would be important for increasing CoFeB thickness to characterize the sign and magnitude of the interlayer exchange coupling. The FMR measurement was conducted for the SyF structure with CoCrPt and CoFeB layers. The CoFeB layer thicknesses $t_{CoFeB}$ were fixed to 3 nm to obtain sufficient signal intensity. Figure 3(a) shows the FMR spectra of that CoFeB films in the single layer deposited on the Ru buffer and in the SyF structures with Ru spacer of $t_{Ru} = 0, 0.4, 0.6, 0.8, 1.2$ nm. Here, $t_{Ru} = 0$ means that CoFeB was deposited directly on the CoCrPt film. Generally, the resonance field, $H_{res}$ of SyF structure should be shifted to a high (low) field when the interlayer exchange coupling is antiferromagnetic, AF (ferromagnetic, F) [8]. The sample with $t_{Ru} = 0.4, 0.6, 0.8$ nm exhibited AF coupling; the other showed F coupling, which was consistent with a magnetization curve measurement. The values of $J_{ex}$ for each Ru thickness were estimated from Kittel’s formula using a resonance field of both CoFeB single layer and SyF structure and effective anisotropy field of CoCrPt. The results were shown in Fig. 3(b). The magnitudes of $J_{ex}$ for AF coupling are in good agreement with the values of magnetization curves (Fig. 2(b)). It turned out that FMR measurement with applied field perpendicular to the film plane can evaluate the interlayer exchange coupling as an interfacial effect independently of the CoFeB thickness. From this calculation, the $J_{ex}$ of F coupling energy for $t_{Ru} = 0$
and 1.2 nm is obtainable unlike magnetization measurement. The value of $J_{ex} = -7.5 \text{ erg/cm}^2$ for $t_{Ru} = 0$ is quite large because of the direct ferromagnetic coupling. Moreover, the strength of the F coupling in $t_{Ru} = 1.2$ nm is similar to the AF coupling in the samples with $t_{Ru} = 0.6$ and 0.8 nm. Although the CoCrPt has a small saturation magnetization and certain nonmagnetic elements, the coupling to CoFeB layer is as large as the SyF structure with two in-plane magnetized layers such as Co/Ru/Co [4], CoFeB/Ru/CoFeB [7] stacking. However, the coupling strength of the SyF structure of CoCrPt/Ru/CoFeB is insufficient. To make 2-nm-thick CoFeB magnetization stand up perpendicular direction, countermeasures of increasing the intensity of exchange coupling and/or reducing saturation magnetization of CoFeB should be devised.

![Figure 3.](image_url)

Figure 3. (a) FMR spectra of the CoFeB in the ferromagnetic single layer (sub./Ta/Ru/CoFeB 3 nm/MgO/Ta) and in the SyF structure of CoCrPt/Ru/CoFeB with different Ru thickness. (b) Dependence of exchange coupling energy on the Ru spacer thickness.

In conclusion, we fabricated a SyF structure consisting of CoCrPt/Ru/CoFeB and observed perpendicular interlayer exchange coupling between two ferromagnetic layers having both perpendicular and in-plane anisotropy. The magnetization curves by VSM and SQUID and FMR spectra exhibited that the dependences of $J_{ex}$ on Ru spacer thickness have the oscillatory behaviors and that the strength of the exchange coupling is consistent with an all in-plane or perpendicular magnetized SyF structure.

Acknowledgements
A Grant-in-Aid for scientific research, NEDO grant, and the Asahi Glass Foundation.

References
[1] Nakayama M, Kai T, Shimomura N, Amano M, Kitagawa E, Nagase T, Yoshikawa M, Kishi T, Ikegawa S and Yoda H 2008 J. Appl. Phys. 103 07A710
[2] Ikeda S, Hayakawa J, Ashizawa Y, Lee Y M, Miura K, Hasegawa H, Tsunoda M, Matsukura F and Ohno H 2008 Appl. Phys. Lett. 93 082508
[3] Watanabe D, Mizukami S, Oogane M, Naganuma H, Ando Y and Miyazaki T 2009 J. Appl. Phys. 105 07C911
[4] Bloemen P J H, van Kesteren H W, Swagten H J M and de Jonge W J M 1994 Phys. Rev. B 50 13505
[5] Parkin S P, More N and Roche K P 1990 Phys. Rev. Lett. 61 2304
[6] Zhao J, Wang Y J, Liu Y Z, Han X F and Zhang Z 2008 J. Appl. Phys. 104 023911
[7] Hayakawa J, Ikeda S, Lee Y M, Sasaki R, Meguro T, Matsukura F, Takahashi H and Ohno H 2006 Jpn. J. Appl. Phys. 45 L1057
[8] Heinrich B, Purcell S T, Dutcher J R, Urquhart K B, Cochran J F and Arrott A S 1988 Phys. Rev. B. 38 12879