Effect of the Pt buffer layer on perpendicular exchange bias based on collinear/non-collinear coupling in a $\text{Cr}_2\text{O}_3/\text{Co}_3\text{Pt}$ interface

T. Ashida,^{a)} Y. Sato, T. Nozaki, and M. Sahashi

Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan

(Presented 15 January 2013; received 5 November 2012; accepted 21 December 2012; published online 29 March 2013)

In this study, we fabricated a Cr_2O_3 (0001) film without and with a Pt buffer layer and investigated its effect on perpendicular exchange coupling in a $\text{Cr}_2\text{O}_3/\text{Co}_3\text{Pt}$ interface. The results showed that the exchange bias field (μ_0H_{ex}) and blocking temperature (T_B) of a Cr_2O_3 film without and with Pt were very different. The Cr_2O_3 film without Pt had a lower μ_0H_{ex} of 176 Oe and a lower T_B of 75 K, whereas that with Pt had a higher μ_0H_{ex} of 436 Oe and a higher T_B of 150 K. We discussed this difference in μ_0H_{ex} and T_B values based on collinear/non-collinear coupling in a ferromagnetic and antiferromagnetic interface using Meiklejohn and Bean's exchange anisotropy model. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4797472>]

I. INTRODUCTION

Crossing correlation between magnetic and electric properties is presented in so-called magnetoelectric (ME) materials, which should be considered for future spintronic devices, such as magnetoelectric random access memory, MERAM.¹ Cr_2O_3 is a well-known ME material and a strong candidate for realizing such devices. Cr spins orient parallel to the [0001] axis and are uncompensated in the (0001) plane. These uncompensated spins produce a perpendicular exchange bias.^{2–5} Recently, the clear ME effect of bulk Cr_2O_3 was observed through an exchange bias.⁴ For Cr_2O_3 to be applied in future spintronic devices, it is first necessary to obtain a sufficient exchange bias field (μ_0H_{ex}) at the Cr_2O_3 /ferromagnet (FM) interface for a Cr_2O_3 film stacked on a metal electrode. Herein, we fabricated a Cr_2O_3 (0001) film without and with a Pt electrode layer (buffer layer) and investigated the structural and magnetic properties.

II. EXPERIMENTAL PROCEDURES

The film design was Al_2O_3 (0001) substrate/ Cr_2O_3 50/ Co_3Pt 3/ Ru 2/ Ta 3 nm (without Pt) and Al_2O_3 (0001) substrate/Pt 25/ Cr_2O_3 50/ Co_3Pt 3/ Ru 2/ Ta 3 nm (with Pt). The Pt buffer layer was deposited by a magnetron sputtering method at room temperature (RT) and then annealed at 873 K to smoothen the surface. The Cr_2O_3 film was grown by an ion beam sputtering (IBS) method in $\text{Ar} + \text{O}_2$ gas at RT and post-annealed at 973 K in an O_2 atmosphere. A Co_3Pt ferromagnetic layer and a Ru/Ta capping layer were deposited by the IBS method at RT. To improve perpendicular magnetic anisotropy, the films were annealed at 573 K in a high vacuum. Structural characterizations were carried out by X-ray diffraction (XRD) and atomic force microscopy (AFM). The magnetic properties of the film were investigated using a superconducting quantum interference device (SQUID). SQUID measurements were carried out after

samples were cooled from 330 K to measurement temperature in a magnetic field of +10 kOe perpendicular to the film.

III. RESULTS AND DISCUSSIONS

Figure 1 shows AFM image of the Cr_2O_3 surface of the film (a) without Pt and (b) with Pt after annealing. As you can see, the morphology of Cr_2O_3 surface of these films is quite different from each other. The roughness of the film without Pt buffer layer was 1.2 nm while that of the film with Pt buffer layer was 0.6 nm. We confirmed the Cr_2O_3 (0001) orientation of the both film without Pt and with Pt by out-of-plane and in-plane XRD measurement.

Here, we discuss the magnetic properties of the films toward the out-of-plane direction. Figure 2 shows the magnetization curves of the film without Pt at (a) 70 K and (b) 200 K and of the film with Pt at (c) 70 K and (d) 200 K. Table I lists the remanence ratio (M_r/M_s), coercive field (μ_0H_c), and μ_0H_{ex} of the films. For both films, we observed M_r/M_s toward out-of-plane direction at 70 K and 200 K. It should be noted that μ_0H_{ex} was not observed at 200 K. The origin of the finite M_r/M_s at 200 K would be magnetocrystalline anisotropy of hcp-type Co_3Pt alloy.⁶ The M_r/M_s of the film without Pt is lower than that with Pt at 200 K. The lower M_r/M_s indicates that the magnetic moment of the FM layer of the film without Pt is oblique from the

FIG. 1. AFM images of the Cr_2O_3 surface of films (a) without Pt buffer layer and (b) with Pt buffer layer after annealing ($2\ \mu\text{m} \times 2\ \mu\text{m}$).

^{a)}Electronic mail: ashida.t@ecei.tohoku.ac.jp

FIG. 2. Magnetization curve of the film without Pt at (a) 70 K and (b) 200 K and the film with Pt at (c) 70 K and (d) 200 K for the out-of-plane direction.

out-of-plane direction. The Cr_2O_3 surface of the sample without the Pt buffer is rough in comparison with that with Pt (see Fig. 1). This rough surface may invoke the low crystal orientations of Co_3Pt and the oblique FM moment. As the spin direction of the Cr_2O_3 (0001) film is perpendicular to the films, the FM spin has a finite angle to and is parallel to the antiferromagnetic (AF) spin for films without and with Pt. Here, we consider the total free energy per unit surface area using the Meiklejohn and Bean's exchange anisotropy model (MB model) for non-collinear FM/AF coupling,⁷⁻⁹ in order to discuss the relation between FM moment direction and $\mu_0 H_{\text{ex}}$. We assume that the FM/AF magnetic moments ($M_{\text{FM/AF}}$) align along the uniaxial anisotropy of the FM/AF ($K_{\text{FM/AF}}$) direction, when $\mu_0 H_{\text{ex}}$ is not present. When $\mu_0 H_{\text{ex}}$ is present, the M_{FM} and M_{AF} are canted α and β degrees from the initial state, respectively, owing to the influence of both applied fields ($\mu_0 H$) and $\mu_0 H_{\text{ex}}$. The vector diagram is shown in Fig. 3. The energy per unit area of an exchange bias system can be written as

$$E = -\mu_0 H M_{\text{FM}} t_{\text{FM}} \cos(\phi - \beta) - \mu_0 H M_{\text{AF}} t_{\text{AF}} \cos \alpha + K_{\text{FM}} t_{\text{FM}} \sin^2 \beta + K_{\text{AF}} t_{\text{AF}} \sin^2 \alpha - J_{\text{ex}} S_{\text{FM}} S_{\text{AF}} \cos(\phi - \beta - \alpha), \quad (1)$$

where $t_{\text{FM/AF}}$, J_{ex} , and $S_{\text{FM/AF}}$ are the layer thicknesses of FM/AF, the interface-exchange coupling constant, and the interface magnetic moments of FM/AF, respectively. α , β , and ϕ are the angles between $\mu_0 H$ and M_{AF} , $\mu_0 H$ and M_{FM} ,

FIG. 3. Vector diagram of angles in an exchange bias system involving angles α , β , θ , and ϕ . H , $M_{\text{FM/AF}}$, and $K_{\text{FM/AF}}$ are the applied magnetic field, the magnetic moment of FM/AF, and uniaxial anisotropy of FM/AF, respectively.

and $\mu_0 H$ and K_{FM} axis, respectively (see Fig. 3). In this model, $\mu_0 H_{\text{ex}}$ is written as

$$\mu_0 H_{\text{ex}} = -\frac{J_{\text{ex}} S_{\text{AF}} S_{\text{FM}} \cos \theta}{M_{\text{FM}} t_{\text{FM}}}, \quad (2)$$

where θ is the angle between M_{FM} and M_{AF} , defined as $\theta = \phi - \beta - \alpha$. Equation (2) indicates that the $\mu_0 H_{\text{ex}}$ decrease with increasing angle θ in proportional to $\cos \theta$. The lower $\mu_0 H_{\text{ex}}$ of the sample without Pt relative to that with Pt is explained by the large angle θ .

Figure 4 shows the temperature-dependent unidirectional magnetic anisotropy energy J_K ($=\mu_0 H_{\text{ex}} M_{\text{S}} t_{\text{FM}}$) of films without and with Pt. Here, M_{S} and $\mu_0 H_{\text{ex}}$ are experimental values, and t_{FM} is 3 nm. J_K appears suddenly at 75 K (without Pt) and at 150 K (with Pt). We call this temperature, blocking temperature (T_B). The sudden onset of J_K occurs when the relation $K_{\text{AF}} t_{\text{AF}} \sim J_{\text{ex}}$ is satisfied.^{5,9,10} Thus, a large T_B is obtained when J_{ex} is small. From the definition of J_K , the relationship between J_{ex} and J_K is formulated as

$$J_K = \mu_0 H_{\text{ex}} M_{\text{S}} t_{\text{FM}} = 2J_{\text{ex}} S_{\text{F}} S_{\text{AF}} \cos \theta. \quad (3)$$

The film without Pt has finite angle θ , while that with Pt has angle $\theta \sim 0$. From Eq. (3), J_K decreases with an increase in θ . However, J_{ex} , which has high correlation with T_B , is θ -independent. Thus, even if $\mu_0 H_{\text{ex}}$ and J_K become smaller

FIG. 4. Temperature dependence of unidirectional magnetic anisotropy energy J_K of film without Pt (●) and film with Pt (★) for the out-of-plane direction.

TABLE I. Values of M_r/M_s , $\mu_0 H_c$, and $\mu_0 H_{\text{ex}}$ of films without and with Pt at 70 K and 200 K.

	M_r/M_s	$\mu_0 H_c$ (Oe)	$\mu_0 H_{\text{ex}}$ (Oe)
Without Pt (70 K)	0.57	584	176
With Pt (70 K)	0.88	1080	436
Without Pt (200 K)	0.45	580	10
With Pt (200 K)	0.87	1496	25

as a result of a large θ , T_B is not changed. Both small $\mu_0 H_{ex}$ and low T_B would be observed in the film without Pt due to the relative large θ . Herein, we discuss the difference of $\mu_0 H_{ex}$ and T_B between films without and with Pt using the non-collinear coupling effect in the MB model. Using this model, we explained that J_K is not always increased when T_B decreased, if the spin directions of FM and AF have finite angle θ . However, the low T_B for the film without Pt was not yet explained. One possibility of the low T_B would be low K_{AF} value for the film without Pt. To discuss the effect of K_{AF} in more detail, further study is needed.

IV. SUMMARY

We fabricated Cr_2O_3 (0001) films without and with Pt buffer layer. The morphology of Cr_2O_3 surface and hence magneto-crystalline anisotropy (spin direction) of Co_3Pt layer changed by inserting Pt buffer layer. The change in spin direction affects the exchange bias ($\mu_0 H_{ex}$) and blocking temperature (T_B) of Cr_2O_3/Co_3Pt interface. We observed $\mu_0 H_{ex} \sim 176$ Oe and $T_B \sim 75$ K (film without Pt) and $\mu_0 H_{ex} \sim 436$ Oe and $T_B \sim 150$ K (film with Pt). We explained the difference of $\mu_0 H_{ex}$ and T_B between films without and

with Pt by the collinear/non-collinear coupling effect between Cr_2O_3 and ferromagnetic magnetic moments.

ACKNOWLEDGMENTS

This research was supported in part by Japan Science and Technology Agency, Advanced Low Carbon Technology Research and Development Program (JST-ALCA).

- ¹X. Chen, A. Hochstrat, P. Borisov, and W. Kleemann, *Appl. Phys. Lett.* **89**, 202508 (2006).
- ²P. Borisov, A. Hochstrat, X. Chen, W. Kleemann, and C. Binek, *Phys. Rev. Lett.* **94**, 117203 (2005).
- ³T. Nozaki, N. Shimomura, T. Ashida, Y. Sato, and M. Sahashi, *IEEE Trans. Magn.* **48**, 4359 (2012).
- ⁴X. He, Y. Wang, N. Wu, A. N. Caruso, E. Vescovo, K. D. Belashchenko, P. A. Dowben, and C. Binek, *Nature Mater.* **9**, 579 (2010).
- ⁵Y. Shiratsuchi, T. Fujita, H. Noutomi, H. Oikawa, and R. Nakatani, *IEEE Trans. Magn.* **47**, 3909 (2011).
- ⁶Y. Yamada, T. Suzuki, and E. N. Abarra, *IEEE Trans. Magn.* **34**, 343(1998).
- ⁷W. H. Meiklejohn and C. P. Bean, *Phys. Rev.* **105**, 904 (1957).
- ⁸W. H. Meiklejohn, *J. Appl. Phys.* **33**, 1328 (1962).
- ⁹J. Nogués and I. K. Schuller, *J. Magn. Magn. Mater.* **192**, 203 (1999).
- ¹⁰M. Tsunoda, Y. Tsuchiya, T. Hashimoto, and M. Takahashi, *J. Appl. Phys.* **87**, 4375 (2000).