Mechanism and functionality of perpendicular exchange bias using α-Cr_2O_3

Exchange bias is an effect that occurs at the interface of ferromagnetic (FM) and antiferromagnetic (AFM) layers. The magnetization of an exchange-biased system is forced in a particular direction against a magnetic-field cycle. This unidirectional nature of the system requires some symmetry breaking of the interfacial spin structure. The exchange bias was discovered more than 50 years ago, but the microscopic mechanism behind this symmetry breaking has been a major subject in this research field. Although the simple theory predicts that the symmetry breaking is caused by the interfacial uncompensated AFM spin that does not reverse with the magnetization reversal of the FM layer, the existence of such spin is still controversial. This is partly because in the intensively studied Co(-Fe)/Mn-Ir system, the interfacial AFM spins can possess many equivalent spin orientations owing to the non-collinear spin alignment of Mn-Ir, and thus, the differently oriented unreversed interfacial AFM spins would be smeared out macroscopically. In this study, we adopted the Pt/Co/α-Cr_2O_3/Pt perpendicular exchange-biased system in which the interfacial AFM spin can be restricted either up or down relative to the surface normal. In this article, we investigated the behavior of the interfacial uncompensated AFM spins detected using soft X-ray magnetic circular dichroism (XMCD) [1].

In practical applications, the exchange bias is utilized in a spin valve, a key element of the read head of hard disk drives. In the conventional devices, once the exchange bias is defined during the film fabrication process, subsequent control is difficult because high-temperature annealing is usually necessary. This constraint means that the conventional exchange bias is a static effect and it also encourages us to develop the isothermally switchable exchange bias that can offer an additional functionality of spin valves. In this article, we also demonstrate the isothermal switching of the exchange bias using a high pulsed magnetic field [2].

The samples, Pt(1.0)/Co(0.5)/α-Cr_2O_3(50, 120)/Pt(20) films grown on α-Al_2O_3(0001) substrates were fabricated in an ultra-high vacuum magnetron sputtering system. The numbers in parentheses represent the thickness of each layer in nanometer units. Soft X-ray absorption spectroscopy (XAS) and XMCD spectroscopy were adopted to detect the weak magnetic signals of the uncompensated AFM Cr spins separately from the strong signals of the FM Co spins. The XMCD measurements were carried out at the soft X-ray beamline **BL25SU**. A total electron yield method was adopted to detect the XMCD signal. For all XMCD measurements, the magnetic field was applied in the out-of-plane direction. For the isothermal switching study, we used the high-magnetic-field XMCD measurement system [3].

Figure 1(a) shows the XAS and XMCD spectra of the Co $L_{2,3}$- and Cr $L_{2,3}$-edges. The spectra were measured at 180 K after cooling in a magnetic field of +4.0 kOe. The spectra shown in Fig. 1(a) are averaged ones recorded under the static magnetic field of ±10 kOe. The XMCD intensity is observed at both Co $L_{2,3}$- and Cr $L_{2,3}$-edges. The Cr XMCD signal supports the presence of the uncompensated Cr spins at the interface with Co. Figure 1(b) shows the magnetic-field dependence of the XMCD intensity, i.e., the element-specific magnetization curve (ESMC), of Cr measured at 180 K. The photon energy was set at that indicated by the arrow in Fig. 1(a). Both horizontal and vertical shifts of the ESMC are clearly observed, as indicated by the broken and dotted lines, respectively. The horizontal and vertical shifts of the curve are attributed to the exchange bias (H_{Ex}) and

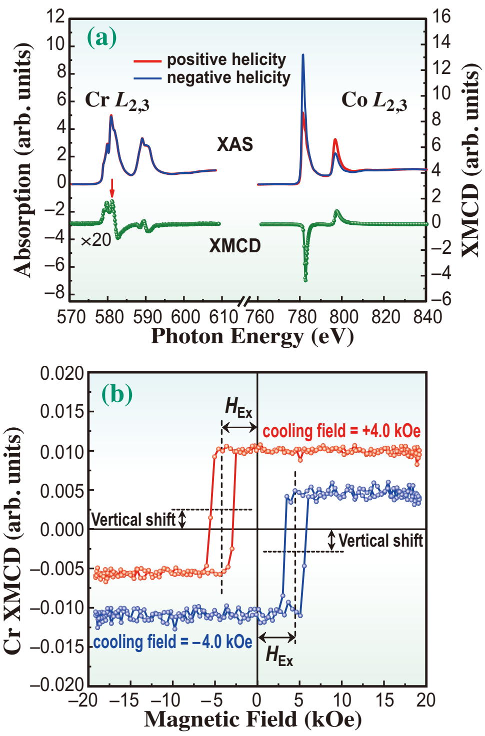

Fig. 1. **(a)** XAS and XMCD spectra at Co $L_{2,3}$- and Cr $L_{2,3}$-edges of Pt/Co/α-Cr_2O_3/Pt/α-Al_2O_3(sub.) film with 120-nm-thick α-Cr_2O_3 layer. **(b)** ESMCs of Cr. Red and blue lines represent the curves measured after applying positive and negative cooling fields, respectively. Broken and dotted lines in (b) represent the exchange bias field H_{Ex} and the vertical shift, respectively [1].

the unreversed uncompensated interfacial Cr spins, respectively. Figure 1(b) also demonstrates that the signs of both horizontal and vertical shifts of the ESMC of Cr are reversed by changing the cooling-field direction. These results indicate the direct relationship between the exchange bias and the unreversed uncompensated Cr spins.

The above finding encourages us to develop the isothermally switchable exchange bias by reversing the usually unreversed interfacial uncompensated Cr spins forcibly by, for example, applying a strong magnetic field. Figure 2(a) shows the ESMCs of Co in the positive pulsed magnetic fields. Measurements were carried out at 77 K after cooling in a negative magnetic field. The photon energy was set at that of the Co L_3-edge. When the maximum field strength was 10 kOe, the XMCD signal, i.e., the Co spin direction, returns to its original orientation after removing the magnetic field owing to the exchange bias. As the maximum applied field strength increases to 80 kOe, the XMCD signal in the remanent state decreases. Finally, the sign of the remanent XMCD is reversed at the maximum applied field strength of 90 kOe. A negative pulsed magnetic field of –10 kOe is subsequently applied and the exchange bias is then observed in the negative direction, as shown in Fig. 2(b). The absolute value of the exchange bias field is conserved after the switching of the exchange bias, meaning that the exchange bias is simply switched from positive to negative. Similar to the case of the positive magnetic field, as the maximum applied field strength exceeds –90 kOe, the exchange bias reverses again from negative to positive. This reversible switching of the exchange bias is qualitatively explained by the spin-flop transition in α-Cr_2O_3 and the exchange coupling between the Co spin and the interfacial uncompensated Cr spin. In Fig. 2(c), the switching process of the interfacial uncompensated Cr spin through the spin-flop excitation is schematically drawn. Assuming that the interfacial uncompensated Cr spins were downward before the application of the magnetic field, after the spin-flop phase is excited by the strong magnetic field above 90 kOe, the interfacial uncompensated spins are reversed to downward during the removal of the magnetic field owing to the interfacial exchange coupling with Co spins. The reversal of the interfacial uncompensated Cr spins causes the switching of the exchange bias. Although, at the present stage, a high magnetic field is employed to switch the interfacial uncompensated Cr spins, another technique with low power consumption and one that is applicable to highly integrated devices will be developed.

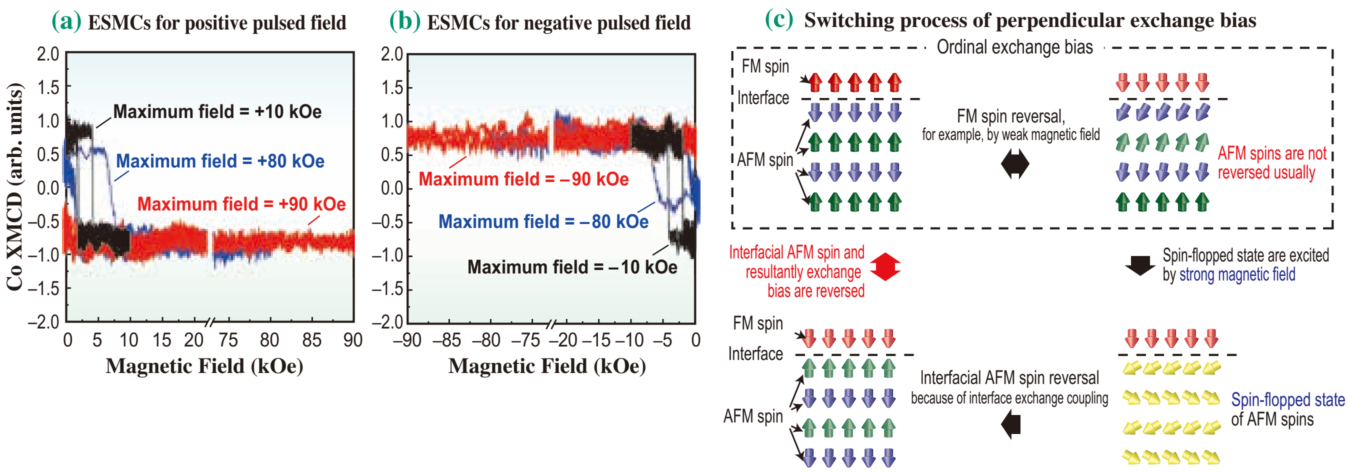

Fig. 2. ESMCs of Co measured under **(a)** positive and **(b)** negative pulsed magnetic fields for the film with a 50-nm-thick α-Cr_2O_3 layer. Black, blue, and red lines represent the curves for the maximum magnetic field strengths of ±10 kOe, ±80 kOe, and ±90 kOe, respectively. **(c)** Schematic representation of the switching process of the interfacial uncompensated Cr spins through the spin-flop transition and accompanying switching of the exchange bias [2].

Yu Shiratsuchi

Department of Materials Science and Engineering, Osaka University

Email: shiratsuchi@mat.eng.osaka-u.ac.jp

References

[1] *Y. Shiratsuchi, H. Noutomi, H. Oikawa, T. Nakamura, M. Suzuki, T. Fujita, K. Arakawa, Y. Takechi, H. Mori, T. Kinoshita, M. Yamamoto and R. Nakatani: Phys. Rev. Lett.* ***109*** *(2012) 077202.*
[2] *Y. Shiratsuchi, K. Wakatsu, T. Nakamura, H. Oikawa, S. Maenou, Y. Narumi, K. Tazoe, C. Mitsumata, T. Kinoshita, H. Nojiri, and R. Nakatani: Appl. Phys. Lett.* ***100*** *(2012) 262413.*
[3] T. Nakamura *et al.*: Appl. Phys. Express. **4** (2011) 066602; SPring-8 Research Frontiers 2011, p.72.