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Isothermal switching of perpendicular exchange bias by pulsed high magnetic field

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Isothermal switching of a perpendicular exchange bias by a strong pulsed magnetic field has been investigated using a Pt/Co/α-Cr_2O_3 thin film system. The switching of the perpendicular exchange bias is accompanied by the spin reversal of interfacial uncompensated antiferromagnetic Cr spins. We have also demonstrated that the switching of the exchange bias is reversible by changing the pulsed magnetic field direction. The mechanism of the demonstrated switching is discussed from the viewpoint of the spin flop transition of the α-Cr_2O_3 layer. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4731643]

Spin-valve film[1] is typically composed of stacked antiferromagnetic (AFM) layer/ferromagnetic (FM) layer/nonmagnetic metallic or insulating layer/FM layer, and it transduces the relative magnetization direction of two FM layers to an electrical resistance change through a giant magneto-resistance effect.[2] The relative orientation of the two FM magnetizations is artificially controlled by stabilizing the magnetization direction of one FM layer in a particular direction. The magnetization of the FM layer attached to the AFM layer is stabilized in a particular direction owing to interfacial exchange coupling between the FM layer and the AFM layer. This effect manifests itself as a shift in magnetization curve along the magnetic field axis and is known as the exchange bias.[3–7] Conventional exchange biases have been induced using Mn-Ir(111) layers as the AFM layer.[8] Once this type of exchange bias is defined during the film fabrication process, the subsequent control of its direction is difficult because high-temperature annealing is usually necessary, which destroys the interfacial magnetic structure because of the high Néel temperature of Mn-Ir alloy. This means that conventional exchange bias is a static effect in these devices. In other words, if the exchange bias can be isothermally controlled in devices, this technique offers an additional functionality of spin-valves, such as a dual input technique that could be used, for example, in the architecture of logic-in-memory devices. Although the isothermal tuning of the exchange bias by means of external parameters such as strong magnetic field,[9–13] ion irradiation,[14] strain,[15] and electric field[16] has been reported, the isothermal switching of the direction of the exchange bias was reported in the limited case.[12,16] Besides, many of these reports are focused on the in-plane directed exchange bias and, in particular, the isothermal switching of the perpendicularly directed exchange bias (PEB) was only achieved using a single crystalline α-Cr_2O_3(0001) substrate.[16] Hence, the isothermal switching of the PEB in all-thin-film system is still a challenging issue. In this paper, we demonstrate the isothermal switching of a high PEB found in a Pt/Co/α-Cr_2O_3 all-thin-film system[17] using a pulsed high magnetic field. We also show the reversibility of the switchable PEB.

Pt(1.0)/Co(0.5)/α-Cr_2O_3(50)/Pt(20) thin film grown on α-Al_2O_3(0001) substrate was used as a sample. The numbers in parentheses represent the thickness of each layer in nm units. The sample was fabricated using an ultra-high vacuum (UHV) magnetron sputtering system, with a base pressure below 7×10^{-7} Pa. The details of this fabrication method can be found in our previous paper.[17] The structure of the sample was characterized by an *in situ* reflection high-energy electron diffraction (RHEED). From the RHEED observations, we confirmed that the crystal orientation of each layer was aligned in the growth direction; Pt(111) ‖ Co(111) ‖ α-Cr_2O_3(0001) ‖ Pt(111).

In this study, a strong pulsed magnetic field was used to switch the PEB. Magnetic measurements were carried out at BL25SU in SPring-8. The switching of the PEB was characterized by the change in the shape of the element-specific magnetization curve (ESMC) with changing maximum magnetic field strength. The ESMC was obtained by measuring the magnetic field dependence of the soft x-ray magnetic circular dichroism (XMCD) signal, which was obtained by the difference in the x-ray absorptions with the positive and negative helicities controlled by twin-helical-undulators. A total electron yield (TEY) method was adopted to detect the absorption signal with the applied voltage of −18 V. The strength of the maximum pulsed magnetic field was varied from 10 to 300 kOe, and its direction was perpendicular to the film. To check the spin orientation of Co and Cr at the remanent state, XMCD spectra were measured at zero magnetic field and a temperature maintained at 77 K. The sample

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was cooled to the measurement temperature in a magnetic field of −5 kOe after first being heated to 320 K, above the Néel temperature of α-Cr_2O_3 (307 K).[18] The details of experimental setup can be found in Refs. 19 and 20.

The soft x-ray absorption spectra (XAS) and XMCD spectra at zero-field for Co $L_{2,3}$- and Cr $L_{2,3}$ edges, just after the field-cooling, are shown in Figs. 1(a) and 1(b), respectively. The XMCD signals are clearly observed for both Co $L_{2,3}$- and Cr $L_{2,3}$ edges, and it is seen that the sign of the XMCD at Co $L_{2,3}$- and Cr $L_{2,3}$ edges are opposite. The XMCD signal at the Cr $L_{2,3}$ edges is generated by uncompensated Cr spins, attributed to interfacial exchange coupling with Co. These results indicate that the interfacial exchange coupling between the uncompensated Cr spins and the Co spins is antiferromagnetic. Deviation of the XMCD spectrum of Cr from the zero base line is due to an artifact of the TEY method. Further details of the XMCD spectrum are reported elsewhere.[21]

Figure 2(a) shows ESMCs of Co in the positive pulsed magnetic fields. The photon energy was set at that of the Co L_3 edge. The differing numbers of data points in the increasing and decreasing branches of the ESMC is caused by the asymmetric shape of the magnetic field pulse.[20] 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. This is attributed to the PEB field being higher than the coercivity.[17] As the maximum applied field strength increases to 80 kOe, the shape of the ESMC begins to change. The XMCD signal at the remanent state decreases, and the sign of the remanent XMCD is reversed at the maximum applied field strength of 90 kOe. Even after reversing the XMCD signal, its absolute value is the same. A negative pulsed magnetic field of −10 kOe is subsequently applied and the PEB is then observed in the negative direction, as shown in Fig. 2(b). The absolute value of the PEB field is conserved after the switching of the PEB, meaning that the exchange bias is simply switched from positive to negative by the pulsed magnetic field. The negative exchange bias is observed for the subsequent measurements as shown in Fig. 2(b). Thus, the switched exchange bias is stable and does not revert to the positive direction for the maximum magnetic field below −80 kOe. When the applied field strength is further increased, the remanent XMCD starts to decrease at the maximum applied field strength of −80 kOe, and it is reversed again at the maximum applied field strength of −90 kOe. It should be noted that the

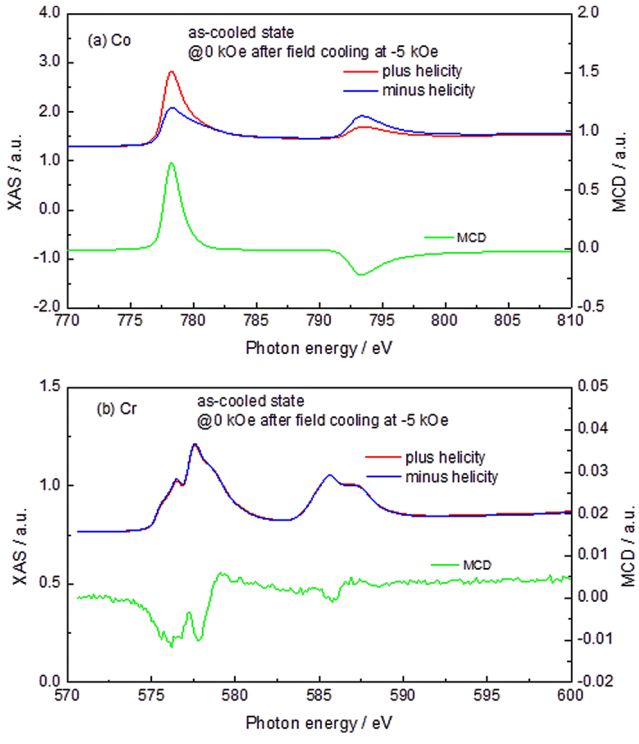

FIG. 1. XAS and XMCD spectra of (a) Co and (b) Cr just after field-cooling in −5 kOe.

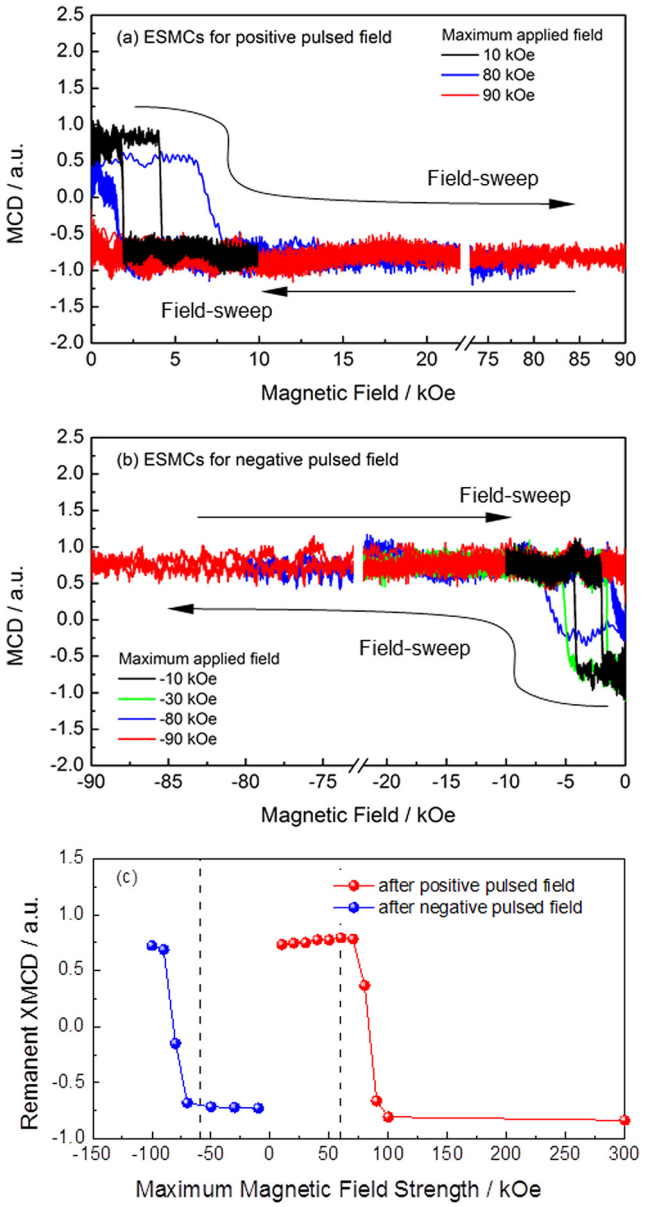

FIG. 2. ESMCs of Co for (a) positive- and (b) negative-pulsed magnetic field. Black, green, blue, and red lines represent the ESMC for maximum applied field strengths of 10 kOe, 30 kOe, 80 kOe, and 90 kOe, respectively. Thin black arrows represent the field-sweep direction. (c) Dependence of remanent XMCD signal with maximum pulsed magnetic field. Red and blue symbols represent the remanent XMCD signal after applying positive- and the negative-pulsed magnetic fields, respectively. The broken lines represent the spin flop field of bulk α-Cr_2O_3.

coercivity for the maximum field of 80 kOe (blue line) is higher than that for the maximum field of 10 kOe (black line). This is because the magnetization reversal of the Co layer cannot follow the fast magnetic-field-sweeping.[22] This effect is well known in the field of magnetic recording and is apparent in magnetic materials of nanometer scale.

Next, we investigate the reversibility of this switchable PEB. The dependence of the remanent XMCD signal at the Co L_3 edge on the pulsed magnetic field strength is shown in Fig. 2(c). As mentioned above, when the positive pulsed field is applied to the film just after field-cooling (red circles), the remanent XMCD signal is almost constant below 70 kOe, begins to decrease at 80 kOe, and switches to a negative value at 90 kOe, i.e., the PEB was switched. After this switching, a negative pulsed field was applied (blue circles). The remanent XMCD signal is then constant up to −70 kOe, begins to increase at −80 kOe, and switches sign at −90 kOe. This correspondence of the switching field of the PEB confirms the reversibility of the switchable PEB and also suggested that the observed switching of the PEB was an isothermal effect.

We confirmed the changes in the spin orientation with the switching of the PEB using XMCD spectra taken at zero fields. XMCD spectra at zero fields after application of a magnetic field of +300(−100) kOe are shown in Fig. 3 as blue (green) lines. The measurement conditions were identical to those of Fig. 1. As compared with the XMCD spectrum shown in Fig. 1, after switching the PEB with the positive pulsed magnetic field, the XMCD spectra for Co and Cr (blue lines) are reversed, as the overall shapes of the spectra are kept except for the fine structure of the Cr L_3 edge and the background in the high energy regime of the XMCD spectrum of Cr. The fine structure of the Cr L_3 edge is explained elsewhere.[21] After the subsequent switching of the PEB by the negative pulsed magnetic field, the XMCD spectra (green lines) are reversed again and become almost the same as the XMCD spectra shown in Fig. 1. These results indicate that the uncompensated Cr spins are isothermally reversed by the pulsed magnetic field and that the switching of the PEB is accompanied by the spin reversal of the interfacial uncompensated Cr spins, which agrees with the switching mechanism proposed for the in-plane exchange biased system.[12]

We discuss the mechanism of the above isothermal switching of the PEB in the viewpoint of the spin flop transition of α-Cr_2O_3. A schematic of a magnetization curve with maximum magnetic field enough to switch the PEB and the corresponding interfacial spin configuration is shown in Fig. 4. It has been reported that the spin flop transition in α-Cr_2O_3 occurs at about 59 kOe below 90 K.[23] In the spin flop state, the Cr spins in the α-Cr_2O_3(0001) layer are oriented in the basal plane of the crystal maintaining the AFM order,[24] and they return to the magnetic easy direction, i.e., up or down, after removal of the magnetic field. When the interfacial uncompensated Cr spins are exchange-coupled with FM(Co) spins, the interfacial uncompensated Cr spin orientation after removal of the magnetic field is determined by the FM Co spin orientation through this interfacial exchange coupling. In the case of Fig. 2(a), the interfacial uncompensated Cr spin orientation was up before application of the pulsed magnetic field, was excited to the spin flop state, and then reversed to down during the removal of the magnetic field, owing to antiferromagnetic interfacial exchange

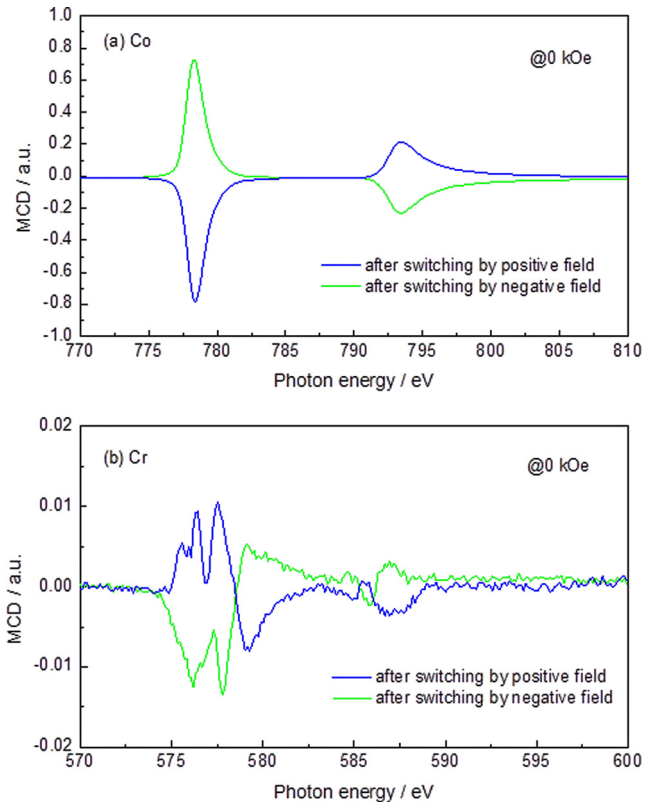

FIG. 3. XMCD spectra of (a) Co and (b) Cr after switching the exchange bias. The blue and green lines represent the spectra after switching the exchange bias using a positive- and the negative-magnetic field, respectively.

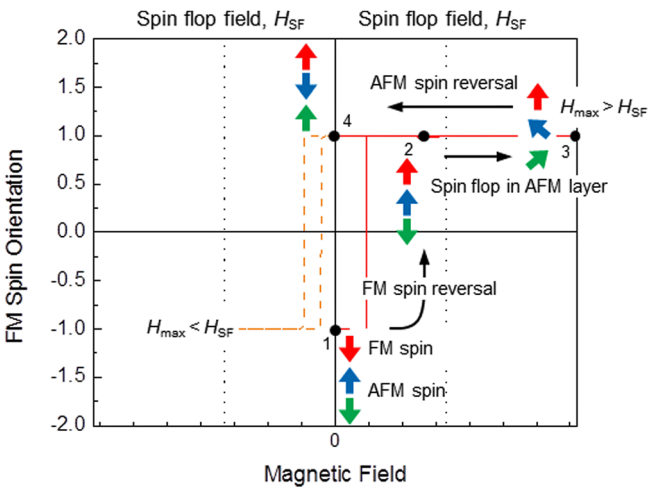

FIG. 4. Schematic representation of the magnetization curve of the ferromagnetic layer. Red solid line represents the magnetization curve for a positive magnetic field strong enough to induce spin flop transition of the antiferromagnetic layer. Orange broken line represents the magnetization curve for a negative magnetic field after switching the exchange bias. Thick color arrows represent the interfacial spin configuration at the various states; 1 as-cooled state, 2 FM spin reversed state, 3 spin flopped state, 4 remanent state after the spin flop. Red arrows represent the ferromagnetic spins. Blue and green arrows represent the antiferromagnetic spins located at the interface and the second layer from the interface, respectively.

coupling with Co spins. The reversal of the interfacial uncompensated Cr spins caused the switching of the exchange bias, indicated by the orange line in Fig. 4. We confirmed that the above mechanism was indeed possible by phenomenological calculations. For comparison, according to this calculation, it is likely that the antiferromagnetic interfacial exchange coupling is not a necessary condition of the isothermal switching of the exchange bias, and it is possible when the interfacial exchange coupling is ferromagnetic.

A quantitative explanation is the remaining problem. As indicated by the broken lines in Fig. 2(c), the magnetic field needed to switch the PEB (~80 kOe) is higher than the reported spin flop field of the bulk α-Cr_2O_3 (~59 kOe). It is known that the spin flop field is sensitive to the relative orientation of the magnetic field and the magnetic easy direction.[25] For the case of the α-Cr_2O_3, the allowed misalignment to observe the spin flop transition will be very small (≈0.015°).[25] Such a small misalignment should occur by the tiny misalignment of the crystal orientation of α-Cr_2O_3(0001) layer, i.e., the quality of the epitaxy[26] or the sample mounting to the instrument or both of them. When the misalignment exceeds the allowable value, the spin axis rotates toward the magnetic field direction gradually. Even in this case, the interfacial uncompensated AFM spins switches in the similar way discussed above as long as the AFM spins are tilted toward the magnetic field direction by enough high magnetic fields. If we consider the intrinsic reason for the increase of the spin flop field, the increase of the magnetic anisotropy energy of the α-Cr_2O_3 layer would be considered. The magnetic anisotropy of α-Cr_2O_3 consists of (1) the magnetic dipolar interaction among the Cr ions, (2) the fine-structure coupling of individual Cr ions, i.e., the spin-orbit interaction combined with the interaction between the orbital angular momentum and the crystalline electric field, and (3) the anisotropic exchange interaction.[27] Among them, the magnetic dipolar interaction and the crystalline electric field may be affected by the epitaxial strain of the α-Cr_2O_3 layer. The XMCD spectra shown in Figs. 1(b) and 3(b) show a prominent miltiplets at Cr L_3 edge compared with the XMCD spectra reported for magneto-electrically cooled bulk α-Cr_2O_3(0001),[28,29] which implies a strong crystalline field at the Cr ion site.

In summary, we demonstrate isothermal switching of a PEB by a strong pulsed magnetic field in a Pt(111)/Co(111)/α-Cr_2O_3(0001) perpendicular exchange-biased system. We also showed that the switching of the PEB is reversible. Based on the phenomenological model, it is suggested that the demonstrated switching of the PEB is triggered by a spin flop of the α-Cr_2O_3 layer.

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