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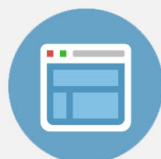
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Simultaneous in-plane and out-of-plane exchange bias using a single antiferromagnetic layer resolved by x-ray magnetic circular dichroism

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We present a study of exchange bias in ferromagnet/antiferromagnet/ferromagnet (FM/AFM/FM) trilayers, with in-plane and out-plane easy axes. Using element-specific x-ray magnetic circular dichroism, we demonstrate that simultaneous in-plane and out-of-plane exchange bias can be induced using a single antiferromagnet and zero field cooling, whereas field cooling only induces exchange bias to the layer with easy axis parallel to the cooling field. Our results further evidence the presence of pinned uncompensated moments in both the FM and AFM layers, implying that the AFM layer is capable of supporting uncompensated spins in two orthogonal directions at the same time. © 2009 American Institute of Physics. [doi:10.1063/1.3232213]

The coupling between ferromagnetic (FM) and antiferromagnetic (AFM) layers that gives rise to exchange bias has been extensively studied.¹ The most prominent effects of FM-AFM coupling are a displacement of the hysteresis loop along the magnetic field axis, H_E , and a coercivity enhancement,¹ which find important applications in magnetic devices.^{2,3} It has been established that both in-plane (IP) and out-of-plane (OP) H_E can be induced in the same FM-AFM stacks.⁴⁻⁸ Moreover, in FM/AFM/FM structures, simultaneous antiparallel or perpendicular IP H_E of the two FM layers has been induced.⁹⁻¹¹ Similar states have been obtained in nanostructured exchange biased systems by exploiting shape anisotropy.^{12,13} To date, although IP FM/AFM/FM systems have been widely investigated,^{9-11,14} only a few studies have been performed on FM/AFM/FM coupling in OP systems.^{15,16} The increase of perpendicularly magnetized elements in magnetic memories and tunnel junctions,^{2,3} as well as the emergence of hybrid IP/OP devices¹⁶⁻¹⁸ has recently exposed the need for simultaneously IP and OP exchange biased layers in a single structure.

Here, we demonstrate that simultaneous IP and OP exchange bias can be obtained by coupling a FM with IP anisotropy ($\text{Ni}_{80}\text{Fe}_{20}$) and a FM with OP anisotropy ($[\text{Co}/\text{Pt}]$ multilayers) to the same AFM layer ($\text{Ir}_{20}\text{Mn}_{80}$). The exchange bias dependence on the cooling procedure provides evidence for the presence of pinned uncompensated spins in both AFM and FM layers when the cooling field is applied parallel to the anisotropy easy axis of the corresponding layer.

A multilayer with composition $\text{Si}(100)/\text{Pt}(2\text{ nm})/[\text{Co}(0.65\text{ nm})/\text{Pt}(2\text{ nm})]_4/\text{Ir}_{20}\text{Mn}_{80}(8\text{ nm})/\text{Ni}_{80}\text{Fe}_{20}(2.6\text{ nm})/\text{Pt}(2\text{ nm})$ was employed as a model system to study directional coupling effects at the two interfaces of the AFM layer, as shown in Fig. 1. The trilayers were grown by dc-magnetron sputtering on thermally oxidized $\text{Si}(100)$ wa-

fers at room temperature. Four samples were cut from the same film and subjected to different cooling conditions after heating up to $T=550\text{ K}$: (i) IP field cooled (FC) with $\mu_0 H_{\text{FC}\parallel}=1\text{ T}$, (ii) OP FC with $\mu_0 H_{\text{FC}\perp}=1\text{ T}$, (iii) zero FC (ZFC) in remanence after IP saturation at $T=550\text{ K}$, and (iv) ZFC in remanence after OP saturation at $T=550\text{ K}$. All samples were characterized at room temperature by superconducting interference device (SQUID) magnetometry. The SQUID hysteresis loops (Fig. 1) exhibit two contributions in both the IP and OP measuring directions, namely a square type of loop superimposed to an "S" shaped loop, consistent with easy and hard axis aligned along the applied field, respectively, as well as significant H_E .

To disentangle the exchange bias contributions, IP and OP element specific hysteresis loops were carried out using x-ray magnetic circular dichroism (XMCD) at the TBT end-station of the Swiss Light Source (SLS). The x-ray energy was tuned to the L_3 XMCD maximum of Fe (NiFe layer), Co (Co/Pt multilayer), and Mn (IrMn layer) and the difference in absorption intensity between right and left polarized light

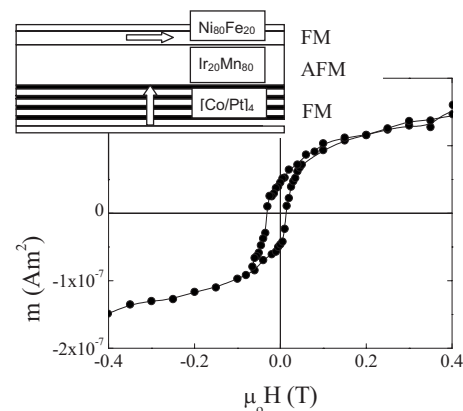


FIG. 1. SQUID hysteresis loop for the sample measured OP after FC OP. Shown in the inset is a schematic diagram of the trilayer structure. The easy magnetization directions are shown by the arrows.

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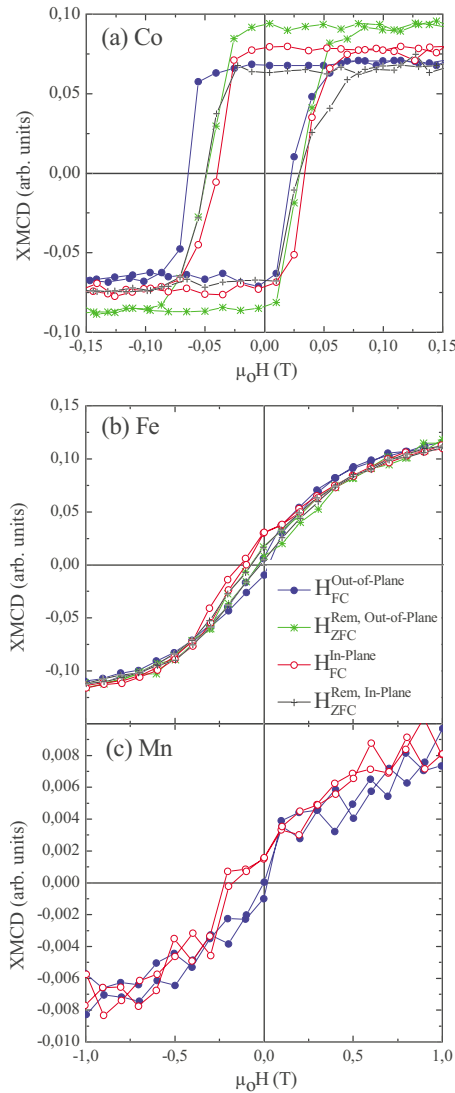


FIG. 2. (Color online) Magnetic loops measured by XMCD at the L_3 of (a) Co, (b) Fe, and (c) Mn edge for the field applied at 10° from the film normal. The four cooling conditions are displayed: out-of-plane FC, $H_{FC}^{\text{Out-of-Plane}}$ (●), ZFC after out-of-plane saturation, i.e., remanence cooled, $H_{ZFC}^{\text{Rem, Out-of-Plane}}$ (*), in-plane FC, $H_{FC}^{\text{In-Plane}}$ (○) and ZFC after in-plane saturation, $H_{ZFC}^{\text{Rem, In-Plane}}$ (+).

was recorded as a function of applied field using total electron yield (TEY) for the near-surface Fe-edge and Mn-edge measurements. Fluorescence yield (FY) was used to record Co-edge loops. Due to geometrical constraints, XMCD in-plane measurements were performed at 20° from the film plane, whereas the out-of-plane ones were performed at 80° , i.e., 10° relative to the sample normal. Note that SQUID measurements carried out at the same angles do not show any significant deviation from 0° and 90° .

Figure 2 shows the element-resolved magnetization loops of the trilayer stack as a function of OP applied magnetic field. The Co loops exhibit easy axis behavior independently on the cooling procedure, with a single-domain state at remanence. Furthermore, the OP FC sample shows the largest H_E , whereas the IP FC sample shows no bias and the samples cooled in IP or OP remanence exhibit moderate H_E . In contrast with Co, all the Fe loops display a hard axis behavior, as expected from the IP easy axis of NiFe. In this layer, the sample FC in-plane exhibits the largest H_E , the two different remanence cooled samples have similar moderate bias, and the OP FC sample has no bias, a behavior that we attribute to the angular dependence of H_E originating from IP

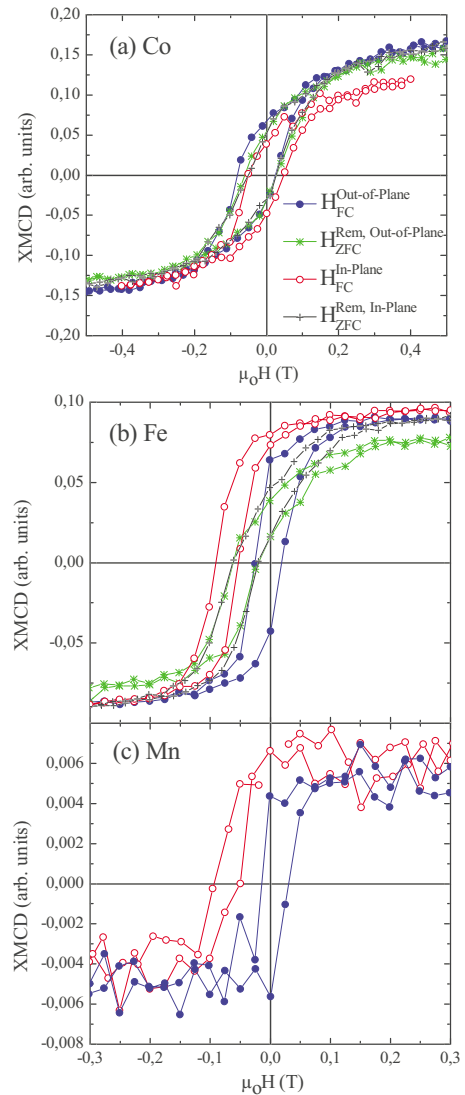


FIG. 3. (Color online) Magnetization loops measured by XMCD at the L_3 of (a) Co, (b) Fe, and (c) Mn for the field applied at 20° from the film plane.

bias,⁸ as explained later. Note that the shape of all the Fe loops in Fig. 2(b) is very similar, indicating that the details of the IP spin structure are not important for the hard-axis measurements.

The magnetization curves measured IP are shown in Fig. 3. Compared to Fig. 2, the Co loops present a hard axis shape, whereas Fe has clearly changed to easy axis behavior. The bias of the Co loops appears to scale with the OP H_E observed in Fig. 2(a), consistently with the angular dependence expected for OP exchange biased structures.^{8,19,20} We find that the largest H_E in the NiFe layer is obtained when FC parallel to the easy axis direction. Hence, opposite to Co/Pt, the Fe loops in Fig. 3(b) reveal significant shifts of the NiFe magnetization for IP FC samples, moderate H_E for both remanence cooling procedures and no bias for FC OP. The Fe loops for the two remanence cooled cases are quite similar, indicating that the remanent state depends more on the shape anisotropy and, possibly, on any minute IP field component due to small field misalignment. The FC loops, both IP and OP, appear rather squared, as expected for an IP easy axis, with moderate shearing that may be induced by a small IP easy axis reorientation due to the IrMn (Ref. 21) or coupling of the NiFe layer to the Co/Pt stack through IrMn.^{22,23} Remarkably, the loops of the remanence-cooled samples

have a more tilted shape compared to the FC specimens. Such a shape may arise from a “dual loop” behavior due to imprinting of the remanent NiFe domain structure in the IrMn during the cooling.²⁴ Note that exchange bias is set by the magnetization state of the FM rather than the cooling field itself.^{9,24}

It is generally accepted that exchange bias originates from the presence of “pinned” uncompensated spins at the AFM/FM interface.^{25,26} The Mn loops in Figs. 2(c) and 3(c) demonstrate the presence of uncompensated Mn spins at the interface with NiFe, the unpinned fraction of which responds to both IP and OP applied fields, essentially following the NiFe magnetization. Note that only the Mn TEY signal, sensitive to the topmost IrMn interface, could be probed, whereas the FY was below the noise threshold. For simplicity, only the two FC cases were measured. The hysteresis loop of the IP FC sample in Fig. 3(c) clearly shows a vertical shift indicating the presence of pinned spins in the IrMn layer. Such vertical shift at the NiFe interface is of the order of $20\% \pm 10\%$ of the total uncompensated Mn magnetization.²⁶ The shift correlates with the magnitude of H_E , and is absent for the OP FC sample.

Differently from previous XMCD measurements,^{26–28} vertical loop shifts are observed also for the FM layers, in particular for the OP Co loops in Fig. 2(a) and IP Fe in Fig. 3(b). Here, we focus on the NiFe magnetization as in the Co/Pt stack the interpretation of such shifts is complicated by the presence of multiple layers.^{4,23} Remarkably, the Fe loop of the IP FC sample measured IP [Fig. 3(c)] exhibits a clear vertical shift of about $8\% \pm 2\%$, whereas none of the other IP loops exhibits a vertical shift greater than 2%.²⁹ Such shift demonstrates the existence of pinned spins in the NiFe layer. This is at first sight surprising since in exchange biased systems it is commonly assumed that the pinned uncompensated spins belong to the AFM.^{24–26} Our data, however, support the analysis of a polarized neutron reflectometry study of FeF₂/Co, which points toward a distribution of pinned spins residing both in the FM and AFM layers.³⁰ The sign of the vertical shift in Fig. 3 is the same for NiFe and IrMn, indicating FM coupling between the pinned Fe and Mn spins.^{26,28,31} For both Fe and Mn, the OP FC sample measured IP shows no vertical shift, in agreement with the corresponding lack of H_E of the NiFe layers in the same configuration. Moreover, the OP measurements for all cooling conditions show no vertical bias, supporting the assumption that the OP H_E for the Fe-edge loops [Fig. 2(b)] arises from the IP H_E and the 80° measuring angle, i.e., is not an intrinsic effect.

When looking at the results as a whole, our measurements reveal that field cooling only induces significant exchange bias in the layer with easy axis parallel to the cooling field, which originates from pinned uncompensated spins in both the FM and AFM layers. The lack of bias in the layer with anisotropy perpendicular to the cooling field implies either that the pinned uncompensated spins generated at the interface are orthogonal to the FM spins³² or that no stable pinned uncompensated spins are generated in this condition. Zero field cooling in remanence brings about *simultaneous* exchange bias to both the NiFe layer, with IP anisotropy, and the Co/Pt multilayer, with OP anisotropy. Importantly, the H_E of each layer is along its corresponding easy axis, implying that the AFM layer is capable of supporting uncompensated spins in orthogonal directions at the same time. Hence, either

a complex AFM wall is formed in the AFM^{10,11,14} or the uncompensated spins can be generated independently from each other at each interface.⁹

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