Suppression of magnetization ripple by exchange bias

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We present a magnetic domain imaging study of polycrystalline exchange biased ferromagnet/antiferromagnet Co/FeMn bilayers using x-ray photoelectron emission microscopy. At low FeMn thicknesses, where the system exhibits no exchange bias, a magnetic fine structure due to fluctuations of the local anisotropy axis is observed in the ferromagnetic Co layer. We find that upon increasing the FeMn layer thickness, this dispersion of the magnetization of the ferromagnetic layer is increasingly suppressed. This can be interpreted as influence of the exchange bias field on the spin structure of the ferromagnetic layer, mediated by the interface coupling, if the "exchange length" (analogous to a domain-wall width) of the antiferromagnetic layer is larger than that of the ferromagnetic layer. The same behavior is observed for both the induced Fe and Mn ferromagnetic moments in the antiferromagnetic layer. We illustrate that the final spin structure at the Co/FeMn interface is not only governed by the magnetic spin structure of the Co layer alone (which is the general perception) but is also an exchange average of both the Co and FeMn layers.

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I. INTRODUCTION

The exchange coupling which exists between the spins of a ferromagnetic (F) and antiferromagnetic (AF) layers gives rise to the well-known exchange bias effect.[1] The most widely recognized manifestations of this phenomenon are the offset of the magnetic hysteresis loop from zero, referred to as the exchange bias field (H_e), and its associated coercivity (H_c) enhancement. In recent years the phenomenon of exchange bias has become the basis of many important technological spintronic devices where the exchange coupling is used to confine the direction of the magnetization of a ferromagnetic layer.[2–4]

Despite 50 years that have elapsed since its discovery, there is still a disparity[5] between the experimentally obtained values for the exchange field and those predicted by simple theories. It is generally acknowledged that the spin structure is the key to the exchange bias effect and that understanding the microscopic spin structure at the interface is the means to unravel the mechanism behind unidirectional anisotropy, coercivity enhancement,[6] temperature and thickness dependencies,[7] along with effects of magnetic training[8] sometimes present in such systems.

Several models have emerged to address theses issues, where the effects of interfacial spin configuration,[9–13] crystal structure,[9,14,15] interface roughness,[11,16,17] anisotropy,[18,19] magnetic frustration,[20] and magnetic domains[9–11,21] have been considered. The latter of these, which involve domains within the AF layer, have shown to be most promising. Mauri *et al.*[10] extended the idea of planar domain walls[22] originating at a smooth AF interface, where the AF spins rotate in the plane. In this case the exchange energy is spread across the width of the domain wall. Subsequent models[23,24] which have further extended the planar wall concept have also shown limited success in fully explaining the exchange bias effect. An alternative approach was put forward by Malozemoff,[11] who argued that an ideal interface was unrealistic and roughness at the interface leads to magnetic defects, giving rise to local random fields. The total energy, including the contribution from the random fields, is minimized by the formation of domains in the AF, which have domain walls perpendicular to the interface. The "domain state model" of Nowak *et al.*[21] showed that diluting the AF layer with random defects gives rise to local moments within the AF domains. The effective fields from these domains are responsible for the exchange field across the interface. The model has been able to describe most key features associated with the exchange bias phenomenon.[25,26] The effects of frustration, along with disorder,[27,28] have been shown to be important factors in such exchange bias systems, and recent studies have favored the idea of the domain state model.

As mentioned earlier, what is paramount to the understanding of exchange biasing is the interfacial spin structure. A recent investigation in epitaxially grown Co/FeMn films has shown that the coupling between the F and AF layers is mediated not by atomically smooth terraces but by atomic step edges and dislocations which generate atomic roughness.[17] It was shown that by controlling the amount of atomic steps at the interface, the coupling properties between the AF and F layers can be greatly influenced. A different AF-F coupling strength, in turn, can give rise to proximity effects influencing the ordering temperature of both the F (Ref. 29) and the AF layers.[30]

The spin structure in polycrystalline ferromagnetic materials is complicated by fluctuations of the magnetic anisotropy resulting from the randomly oriented easy axes of magnetization of the individual grains. This leads to the so-called magnetic ripple, a magnetic fine structure first observed by

Lorentz microscopy in the 1960s.[31–33] The local magnetization direction undulates around the macroscopic magnetization direction by a certain amplitude and wavelength, which depend on the mean grain size, the magnetic anisotropy, film thickness, exchange constant, saturation magnetization, and an externally applied magnetic field.[34,35]

The general perception within the magnetism community is that the ferromagnetic layer plays the key role in determining the magnetic spin structure in an exchange biased system, where the Curie temperature of the F is significantly larger than the Néel temperature of the AF. In this paper we present results contrary to this belief, where it is shown that both the F and AF layers are involved in determining the magnetic spin structure in exchange bias systems. We find that depending upon the relative exchange lengths of the respective layers, the exchange bias field that shifts the hysteresis loop macroscopically can have the same effect on the magnetization dispersion of a polycrystalline ferromagnet with random anisotropy axes as an external field. By tuning the exchange bias field by the thickness of the AF layer, we find that the amplitude of the magnetic fine structure in the F layer decreases. While often only the influence of the magnetization of the F layer on the spin structure of the AF layer is discussed, our findings show that in the case of a noncollinear rapidly spatially varying spin structure in the ferromagnet the reverse case can be also present and has to be taken into account.

II. EXPERIMENTAL TECHNIQUES

Ta(50 Å)/Cu(60 Å)/$Fe_{50}Mn_{50}$(25–50 Å)/Co(20 Å)/Cu(118 Å)/Ta(100 Å) specimens were sequentially deposited onto Si(001) substrates by dc-magnetron sputtering at an argon working pressure of 2.5 mTorr. Typical deposition rates were 2–2.5 Å/s, which were determined by measuring the thickness of calibration films by low-angle x-ray reflectometry. An in-plane forming field of 200 Oe was applied during the growth to induce a macroscopic uniaxial anisotropy in the Co layer in a defined direction. The base pressure prior to the deposition was of the order of 1×10^{-8} Torr and the samples were deposited at ambient temperature. The $Fe_{50}Mn_{50}$ layers were deposited from an alloy target. The thickness of the FeMn layer, t_{AF}, was varied in the region where the onset of biasing appears at room temperature. To facilitate the growth of face-centered-cubic (fcc) (111) orientation of FeMn, a buffer underlayer of Ta and Cu was employed. X-ray diffraction revealed that such samples were predominantly fcc with a (111) texture. No influence of the FeMn layer thickness on the structure and grain-size distribution of the Co layer could be observed.

The specimens were heated to 300 °C in a vacuum furnace (1×10^{-6} Torr) for 10 min and zero-field cooled through the Néel temperature (T_N) of 200 °C. Prior to the cooling, the Co layer was initially ac demagnetized along the mean uniaxial anisotropy axis which had been set during the deposition. In this manner a multidomain structure is generated with a remanence value close to zero. Two opposite unidirectional anisotropy directions are generated leading to double-shifted hysteresis loops in opposite directions.[36] Measurements normal to this axis revealed no shifted loops. To prevent oxidation of the specimens a protective cap of Cu and Ta was used. It has been shown previously[26] that any changes induced by the heating procedure in the magnetic properties were insignificant. It should be noted that the demagnetizing process is necessary to ensure that the Co is not in its remanent state in order to observe a domain pattern in the photoelectron emission microscopy (PEEM) measurements. No domain structure would be visible if the domains were larger than 40 μm, which is the field of view of PEEM.

The insertion of Cu between the Co layer and the Ta cap layer was to aid the PEEM measurements of the uncompensated Fe and Mn moments. A cleaner electron yield signal is obtained through the Cu than the Ta, which was sputtered away *in situ* before commencing the measurements. Magnetic characterization was done using a vibrating sample magnetometer (VSM) (results not shown here) and magneto-optical Kerr effect (MOKE). Element-resolved magnetic domain imaging by PEEM along with x-ray magnetic circular dichroism (XMCD) was performed at the helical undulator beamline UE56/2-PGM1 of BESSY in Berlin. Circularly polarized light with a degree of polarization of about 80% was incident on the sample at a 60° angle measured from the surface normal. The setup of the electrostatic photoelectron emission microscope (Focus IS-PEEM) is identical to that described in previous publications.[37] In summary, it consists of an electrostatic straight optical axis microscope with an integral sample stage and a variable contrast aperture. The magnified image is intensified by a two-stage microchannel plate and converted into visible light by means of a scintillator crystal. The image is then computer recorded with 12 bit resolution by a Peltier-cooled camera (PCO SensiCam), which was operated with 2×2 binning of pixels. Parameters were set to result in a lateral resolution of 300 nm and a field of view of 40 μm. Images are presented in the form of grayscale-coded absorption asymmetry upon helicity reversal of the exciting radiation, i.e., the difference of two images acquired for opposite helicity divided by their sum. Images were taken at the maxima of the Co, Fe, and Mn L_3 edges, respectively. For the PEEM measurements the sample was rotated in such a way that the x-ray incidence was at a 25° azimuthal angle from the easy axis.

III. RESULTS AND DISCUSSION

Figure 1 shows room-temperature MOKE loops for three different FeMn layer thicknesses of interest. For $t_{AF}=25$ Å the Co layer is free to reverse unhindered and exhibits the magnetic characteristics of a single Co layer [Fig. 1(a)]. In this case T_N is below room temperature and the FeMn is in its paramagnetic phase. Whereas, for $t_{AF}=32.5$ Å [Fig. 1(b)], there is a noticeable change in both the shape and coercivity of the loop. One is just able to distinguish that the Co layer is biased in opposite directions. This is clearly evident in the loop shown in Fig. 1(c) where T_N is above room temperature. This elegantly illustrates that the FeMn has ordered onto the Co domain structure which was induced at 300 °C by the ac demagnetizing procedure.

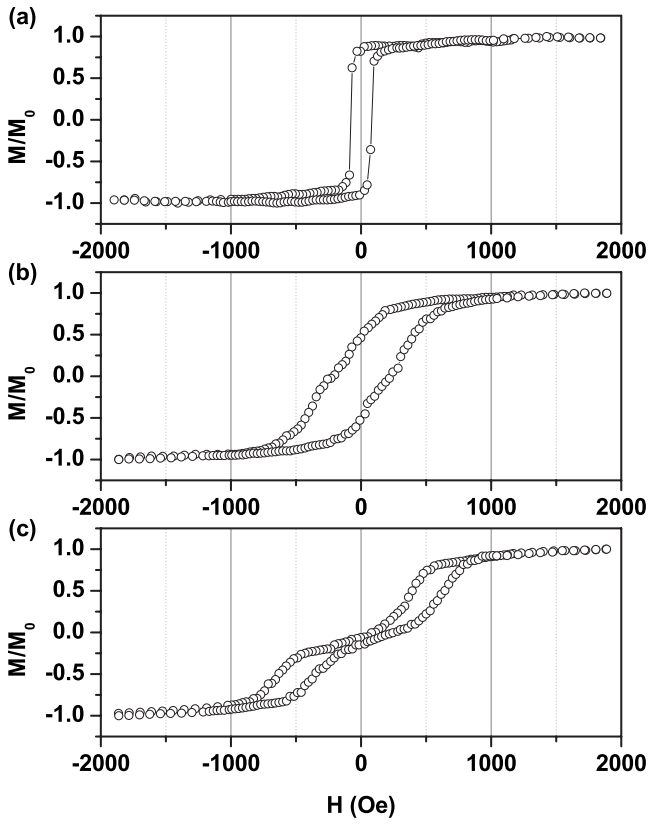

FIG. 1. MOKE loops of the FeMn/Co system for three FeMn layer thicknesses at room temperature normalized to the saturation magnetization M_0. (a) t_{AF}=25 Å, (b) t_{AF}=32.5 Å, and (c) t_{AF} =48 Å.

The dependence of H_e and H_c on the FeMn thickness is shown in Fig. 2. It is found that the onset of exchange bias occurs at approximately 30 Å. Accompanying the onset of biasing is a peak in H_c, which is a general characteristic feature seen in many exchange biased systems.[5,7] The solid lines in both cases are guides for the eyes. It should be noted

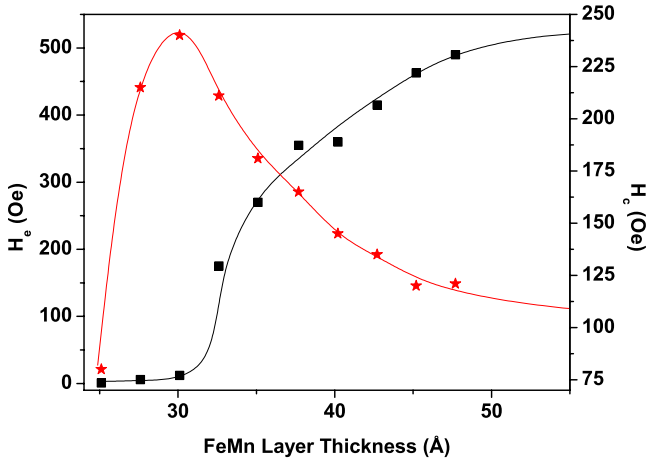

FIG. 2. (Color online) H_e (squares) and H_c (stars) as a function of the FeMn layer thickness at room temperature. H_e and H_c were determined by taking an average for loops which had two segments. The solid lines are guides for the eyes.

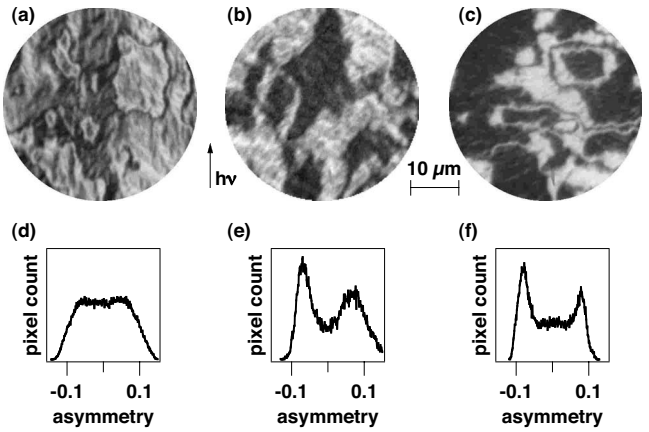

FIG. 3. Co domain images and corresponding histogram plots of the XMCD asymmetry for FeMn thickness [(a) and (d)] t_{AF} =25 Å, [(b) and (e)] t_{AF}=32.5 Å, and [(c) and (f)] t_{AF}=48 Å. The grayscale ranges from −0.15 to +0.15, referring to the raw asymmetry for saturated black and saturated white contrasts.

that both H_e and H_c become constant with FeMn thickness at approximately 60 Å.[7]

Before the onset of any biasing it is clear that there is exchange interaction between the Co and FeMn layers due to the enhancement in H_c around 26 Å FeMn thickness. This value is somewhat higher compared to single-crystalline FeMn/Co bilayers on Cu(001), where a similar enhancement in H_c at room temperature has been observed at about 18 Å.[38] This discrepancy is attributed to a different roughness of the FeMn layers in the present study.

It is accepted that the enhancement in H_c is due to a reversible magnetic component,[39] whether it be domains in the AF or uncompensated spins at the AF-F interface. We have shown previously[7] that for t_{AF} less than 25 Å, the FeMn layer is in its paramagnetic phase at room temperature and there is no enhancement in H_c. Just above this thickness the FeMn begins to order antiferromagnetically. Initially the anisotropy, K_{AF}, of the FeMn layer is not sufficient to withstand the torque experienced by the coupling to the Co spins and the FeMn spins are dragged together with the reversing Co spins. As t_{AF} increases, the anisotropy associated with FeMn develops further, which allows more of the domains/spins to lock together, giving rise to the peak in H_c. At this stage one also observes the emergence of a biasing field. For further increases in t_{AF}, H_c begins to fall as K_{AF} is fully established—fewer spins are able to reverse. It is at this point, where both H_c and H_e become constant with t_{AF}, that the reversible component is no longer changing.

Figure 3 shows typical magnetic domain images of the Co layer for the same three FeMn layer thicknesses for which loops are presented in Fig. 1. Bright and dark contrasts correspond to local magnetization directions parallel and antiparallel, respectively, to the x-ray incidence direction, indicated by an arrow in Fig. 3. Panel (a) shows the domain structure of the bilayer with 25 Å of FeMn. At that thickness, the FeMn layer is in a paramagnetic state at room temperature, as confirmed by the lack of bias in Fig. 1(a). A domain pattern with domains of up to 10 μm size is observed, superimposed by a finer ripple pattern on a submi-

cron length scale. Such a ripple structure is typical for domain images of polycrystalline samples of intrinsic high magnetic anisotropy, such as Co. It is attributed to the competition between the random spatial orientation of the magnetic easy axes of the individual grains about the macroscopic easy axis and the strong ferromagnetic coupling between neighboring grains, which leads to a complex variation in the magnetization along the sample surface as observed in Fig. 3(a).[31–33,40]

A similar but much weaker ripple structure is recognized in Fig. 3(b) for 32.5 Å FeMn thickness. In this sample the FeMn thickness is such that there is already local exchange bias, as judged from the MOKE magnetization loop [Fig. 1(b)]. If the FeMn thickness is further increased to 48 Å, the exchange bias field H_e increases [Fig. 1(c)] and the ripple structure in the Co domain pattern has nearly vanished [Fig. 3(c)]. Instead, the domain pattern exhibits large domains including some ringlike and narrow channel-like structures, which result from laterally inhomogeneous coercivity during the ac demagnetization of the sample. The black and white domains indicate now the local exchange bias directions. Figure 3(c) represents the remanent state of that sample, which is characterized by about zero macroscopic remanence [Fig. 1(c)].

The weakening of the ripple domain pattern with increasing FeMn thickness is also evident from histogram plots of the images. Figures 3(d)–3(f) show histograms of the image intensity of the corresponding domain images (a)–(c). It is clearly seen how the width of the two peaks corresponding to positive and negative XMCD asymmetries, or black and white contrasts in the domain images, is getting narrower as the FeMn thickness is increased. In addition, the contrast between the bright and dark domains, i.e., the position of the two peaks in the histogram plots, shows an apparent increase. If the amplitude of the ripple structure stayed the same, and only the wavelength was reduced below the lateral resolution of the microscope, one would expect a reduced contrast, as is partly the case in Fig. 3(a). The result of Fig. 3 therefore shows that it must be the amplitude of the magnetization dispersion which is reduced with increasing FeMn thickness or with increasing H_e.

Obviously the suppression of the ripple structure in the Co domain pattern is related to the size of the exchange bias field. Theoretically, a decrease in the ripple amplitude is expected for an increasing externally applied magnetic field along with a decrease in the mean wavelength.[34] One could thus be tempted to explain phenomenologically the suppression of the ripple structure simply by the action of the exchange bias field H_e on the polycrystalline F layer. Microscopically, however, one has to consider the situation during the cooling through the Néel temperature of the AF layer. We assume that the spin structure of the Co layer after the ac demagnetization at 300 °C is the same for all samples. This is not an unreasonable assumption since all the samples were ac demagnetized together. The different behavior seen in Fig. 3 has then to be induced during the cooling through the Néel or the blocking temperature of the AF layer. This means that the spin structure of the antiferromagnet, which determines the local exchange bias direction, is thus not identically following that of the ferromagnet, otherwise the ripple structure would just be frozen in by the unidirectional anisotropy, as has been observed, for example, for vortex spin structures in circular disks.[41] In such a case the domain pattern at room temperature should show comparable ripple amplitudes for all samples, which is however not the case. We are unaware of any literature which has previously shown this effect.

The local exchange bias direction has to be smoothed out by some kind of exchange averaging. The local exchange bias direction, determined by the spin structure of the AF layer, is an average over the ripple spin structure of the F layer. Locally dispersing spins in the Co layer experience thus an exchange bias field along an average direction, which in turn leads to the observed suppression of the ripple structure in the Co layer after cooling the AF-F bilayer.

A measure of the exchange lengths can be obtained from determining the values of the domain-wall widths[42] (DWWs) $\delta \propto \sqrt{A/K}$ for the respective layers, which involve the exchange stiffness A and the magnetic anisotropy parameter K. There is a delicate balance between A which tends to increase the exchange averaging and K which has the reverse effect. For the suppression of the ripple structure the DWW and hence the exchange length of the AF layer needs to be larger than that of the F layer. The orientational dispersion of the spins of the AF layer is then less than that of the uncoupled F layer. The high anisotropy of Co could thus be one of the important ingredients for the suppression of the ripple structure by exchange bias. Using typical values for FeMn (Ref. 43) ($K=1.3\times10^4$ J/m^3 and $A=4.1\times10^{-12}$ J/m) and Co (Ref. 44) ($K=5.3\times10^5$ J/m^3 and $A=1.3\times10^{-11}$ J/m), the domain-wall widths are found to be 280 Å for FeMn whereas it is only 77 Å for Co.

It should be noted that the opposite case has also been reported, namely, the occurrence of a noncollinearity or magnetization dispersion in the F layer induced by the exchange interaction with an AF layer in Fe/MnF_2 bilayers.[45] Roughness at the interface may, in the case of a magnetically harder AF layer, lead to a fanning out of the spins of the F layer in response to a fluctuating interface pinning, which is partly averaged out in the F layer. We suggest that in this case the DWW of the AF layer is smaller than that of the F layer, and this is evident in the corresponding calculated DWWs for the respective layers. For Fe (Ref. 46) ($K=4.8\times10^4$ J/m^3 and $A=1.49\times10^{-11}$ J/m) one obtains 391 and 32 Å for MnF_2 (Ref. 47) ($K=4.6\times10^5$ J/m^3 and $A=9.5\times10^{-13}$ J/m).

Induced ferromagnetic moments in the antiferromagnet in AF-F bilayers are often discussed in connection with the AF-F coupling at the interface. Such induced moments can be conveniently detected by XMCD by virtue of its element selectivity. Figure 4 shows the magnetic domain images at the same position of the sample with $t_{FeMn}=48$ Å as in Fig. 3(c) that are obtained if the photon energy is tuned to the (a) Fe and (b) Mn L_3 absorption edges. Although the magnetic contrast is weaker compared to the Co XMCD, the same domain pattern as in Fig. 3(c) is clearly recognized. This means that some of the Fe and Mn moments are aligned together with the Co moments. The same was also found in the samples for the other FeMn thicknesses.

The presence of induced magnetic moments is a quite common observation in AF/F bilayers[48–50] and not necessarily related to the occurrence of exchange bias or the presence

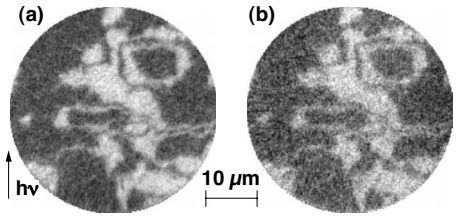

FIG. 4. (a) Fe domain image for t_{AF}=48 Å. (b) Mn domain image obtained from the identical sample position as Fig. 3(c). The full grayscale in (a) Fe is from −0.025 to +0.025 and in (b) Mn from −0.0125 to +0.0125 in asymmetry.

of antiferromagnetic order in the AF layer.[49] Intermixing at the interface may also enhance the amount of induced magnetic moments. It is presently believed, though, that a small fraction of these moments (a few percent in the case of sputter-deposited bilayers[50]) remains pinned in a fixed direction upon magnetization reversal of the F layer, and such causes the exchange bias. The similarity of the domain patterns of the F layer and the induced moments in the AF layer suggests that the same ripple suppression as in the F layer is also present in the induced moments in the AF layer.

IV. CONCLUSION

Depending on the properties of the ferromagnetic and antiferromagnetic layers exchange coupled together in an AF-F bilayer, the collinearity of the spin structure of the ferromagnetic layer may be enhanced by the coupling to an antiferromagnet. In the example presented here the magnetic ripple structure resulting from the polycrystalline nature of the high-anisotropy ferromagnetic Co layer is suppressed by the exchange bias field of the adjacent FeMn layer. We suggest that the decisive factors are the exchange lengths of the two layers, represented by their domain-wall widths. If the domain-wall width of the antiferromagnet is larger than that of the ferromagnet, the domain structure that is frozen into the spatial distribution of the local exchange bias is not exactly that of the free ferromagnetic layer but an exchange-averaged copy. The importance of this finding is the clear demonstration that it is not the ferromagnetic layer alone that is responsible for determining the spin structure in exchange bias systems. This effect may be useful for the creation of polycrystalline or granular high-anisotropy materials with high collinearity of the spin structure.

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