Exchange bias flop in $Fe_xZn_{1-x}F_2$/Co bilayers

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We have measured the angular dependence of the exchange bias field (H_E) in polycrystalline Co thin films deposited on antiferromagnetic (AF) $Fe_xZn_{1-x}F_2$ (110) films. Single crystals and twinned AF samples were studied, the latter possessing small grains (~7.0 nm) with their in-plane [001] easy axes perpendicular to each other. The twinned samples were field cooled through the AF Néel temperature with the field at an angle α with respect to the twins' perpendicular bisector in the plane of the sample. The most negative H_E occurred at an angle $\phi=0$ for $0\leqslant\alpha\leqslant 30°\sim 40°$. An exchange bias flop occurred if α was increased further, where ϕ abruptly shifted by 90°. This means that two equivalent exchange bias field axes exist in this system. A 1.0-nm pure FeF_2 layer deposited between the $Fe_xZn_{1-x}F_2$ and Co layers resulted in a sharper exchange bias flop transition, indicating that the pure interface layer acts as a buffer for the interface interaction. In untwinned FeF_2 samples, a large H_E was observed with the sample field cooled along the FeF_2 easy axis, whereas two loops with the same exchange bias magnitude but of opposite sign were observed when the cooling field was applied 90° to the AF easy axis. Changing the cooling field direction to 91° caused the sample to acquire a significant positive H_E parallel to the AF easy axis. These experiments demonstrate two important notions: (1) that the interface exchange coupling responsible for H_E is extremely sensitive to the underlying magnetic anisotropy of the AF; and (2) that the direction of the cooling field does not necessarily determine the direction of H_E.

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I. INTRODUCTION

Exchange anisotropy originates from the interaction at the interface between antiferromagnetic (AF) and ferromagnetic (F) materials when the AF/F system is field cooled through the AF Néel temperature T_N. There is significant interest in this effect because of the technological applications in magnetic sensor and magnetic random access memory applications.[1] Early magnetic torque measurements in polycrystalline Co/CoO showed that the unidirectional exchange anisotropy energy can be written as $U_A=-K_E\cos\theta$, where K_E is the unidirectional, interface anisotropy energy, and θ is the angle with respect to the cooling field.[2] To first order in $\cos\theta$ the observed shift of the hysteresis loops in AF/F bilayers due to U_A can be written as $H_E=-K_E\cos\theta/M_Ft$, where M_F and t are the magnetization and thickness of the ferromagnet, respectively.[3] The exchange bias H_E is also a measure of the AF/F interface coupling and therefore can be used to determine the antiferromagnetic surface order parameter.[4,5] Hence, this phenomenon is a probe of interface magnetic exchange interactions that are otherwise difficult to measure.

The original model proposed by Meiklejohn and Bean qualitatively explains how H_E depends on the intrinsic magnetic properties by assuming an interface that is fully uncompensated (i.e., antiferromagnetic surface with a net magnetization) and therefore direct exchange AF/F interface coupling.[2] This model fails to explain the existence of exchange bias observed in nominally fully compensated surfaces and surfaces with atomic-scale disorder that would tend to destroy H_E, nor does it reproduce the quantitative value of H_E, which is always much smaller than the value predicted by the theory.[1] Recent x-ray photoemission electron microscopy measurements suggest that the formation of an ultrathin alloy layer at the AF/F interface could cause AF compensated surfaces to have a net magnetic coupling to the ferromagnet.[6]

The angular dependence of H_E and the coercivity H_C were recently used to demonstrate that in general H_E does not have a simple $\cos\theta$ dependence in polycrystalline systems. The maximum H_E occurs at $\theta=\pi/4$ or $\theta=-\pi/4$ in NiFe/CoO bilayers,[3] whereas an in-plane fourfold symmetry is induced in Fe/MnPd bilayers after field cooling.[7] On the other hand, a pure $\cos\theta$ term is adequate for bilayers using amorphous $Co_{65}Mo_2B_{33}$ as the F layer, presumably due to the suppression of the magnetic anisotropy in the F layer.[8] It has also been demonstrated that there is an asymmetric angular dependence of the exchange-coupling direction on the applied field direction in polycrystalline CoO/Co bilayers due to a rotatable anisotropy.[9] It was also recently pointed out that the complex angular dependence of H_E in polycrystalline bilayers can be explained by inhomogeneous AF/F interface coupling, possibly as a result of AF domain wall formation during the F magnetization reversal.[10]

In order to quantitatively understand the magnitude of H_E, models that rely on the formation of domain walls within the AF have been proposed.[11] Some models assume that AF domains are formed during the cool-down procedure, in such a way that a net interface coupling results between the AF and the F at low temperatures.[12,13] This could occur in systems with AF magnetic uncompensated surfaces and rough AF/F interfaces. In general these models predict H_E values that are much closer to those observed experimentally, but the question remains how the domain structure in the AF layer changes as a function of the cooling field direction. Malozemoff's model, for example, seems to imply that this is the case.[12] Experimental evidence supporting the domain state model was recently provided by an observed enhancement of H_E by up to a factor of three in $Co_xMg_{1-x}O$/CoO(0.4 nm)/Co bilayers over the H_E of pure

CoO/Co bilayers.[14] This enhancement presumably results from the creation of AF domains during the cool-down process, facilitated by the nonmagnetic impurities that lower the energy required to form AF domain walls. These small AF domains result in a net magnetic moment at the edges of the AF domains with a net magnetization which couple to the ferromagnet.[13] Subsequently we demonstrated that H_E increases in $Fe_xZn_{1-x}F_2$/Co bilayers with respect to the pure FeF_2/Co system by as much as 65%, as long as a 1.0 nm pure FeF_2 layer is deposited between the dilute AF and F layers.[15]

The main advantage of the $Fe_xZn_{1-x}F_2$ system lies in its crystallographic unit cell, with its rutile, body-centered tetragonal structure, which results in a strong magnetic uniaxial anisotropy along the *c* axis. Therefore, unlike cubic antiferromagnets such as the transition-metal oxides, $Fe_xZn_{1-x}F_2$ has a single axis along which the spins order at low temperatures. Because of this, $Fe_xZn_{1-x}F_2$ is considered to be a realization of the random-field Ising model.[16] Regarding the pure FeF_2 system, it is known that the largest exchange bias in FeF_2/Fe bilayers occurs in (110) FeF_2 twinned samples with two in-plane (001) domains[17] when the cooling field is along the perpendicular bisector of those twinned domains. In (110) FeF_2 (untwinned) single crystals the coupling to the Fe layer is perpendicular to the AF easy axis.[18]

In this paper we study the angular dependence of exchange coupling in twinned $Fe_xZn_{1-x}F_2$/Co bilayers, as well as the exchange bias dependence on cooling field direction in a single-crystal FeF_2/Co bilayer. We show that the exchange bias H_E, the coercivity H_C, and the remanence M_R remain largely unchanged when the direction of the cooling field, α, is changed with respect to the perpendicular bisector of the twins by 30° in the pure sample and dilute samples, and 42° in dilute AF samples with a pure 1.0-nm ultrathin FeF_2 layer deposited between the AF and F. A further increase in α results in a sudden shift (flop) of the maximum H_E position by 90°. This shows that the effective unidirectional magnetic anisotropy generated during the cool-down procedure at the AF/F interface is extremely robust with respect to the cooling field, presumably as a result of the large uniaxial magnetic anisotropy in the bulk of the AF. In twinned AF samples the exchange bias flop occurs due to the existence of two equivalent AF easy axes. We also observe an increase in sharpness of the transition in samples with the ultrathin pure interface layer due to the AF surface ordering at a slower rate than the bulk during the field-cooling procedure, thus insulating the bulk of the AF from the strong exchange interactions generated at the AF/F interface. In untwinned FeF_2/Co bilayers, cooling along the AF easy axis results in the largest H_E, whereas cooling perpendicular to it results in double loops with equal magnitudes of H_E but opposite signs. A misorientation of the cooling field of just 1° with respect to the perpendicular direction produces a large net exchange bias field along the AF easy axis. Domain-state models that seek to quantitatively explain the origin of exchange bias must therefore take into account the anisotropy in the bulk of the AF.

II. EXPERIMENTAL DETAILS

The details of the growth procedure and structural characterization are described elsewhere[15] and are summarized here. The dilute AF (DAF) layers, 68 nm thick, were grown via molecular-beam epitaxy coevaporation of FeF_2 and ZnF_2 at a rate of ~0.02 nm/s and a temperature of 297° C. A polycrystalline Co layer, 18 nm thick, was deposited on top of the dilute AF at a temperature of 125° C, followed by 5.0 nm of MgF_2 to prevent oxidation of the Co layer. Some samples had an ultrathin 1.0-nm pure AF (PAF) FeF_2 layer deposited between the DAF and the F layers. Reflection high-energy electron diffraction showed the presence of two equivalent crystallographic domains. An out-of-plane x-ray diffraction scan, with the scattering vector **q** parallel to the growth direction, was performed to determine the (110) lattice constant of the DAF layer, followed by an in-plane scan of the (332) peak to determine the *c*-axis lattice parameter. This procedure allowed the determination of the Fe concentration x with a precision of ± 0.01. The roughness of the AF/F interface, determined from x-ray reflectivity, was less than 0.8 nm. The in-plane structural coherence was ~6 nm–10 nm, calculated from Scherrer's equation for the (110) and (332) reflections using a method previously used for $Fe_xZn_{1-x}F_2$ (001) films grown on MgF_2 (001).[19] For comparison purposes, an untwinned (110) FeF_2 film was grown on a (110) MgF_2 single-crystal substrate. All other growth parameters, including film thickness, were identical to the twinned samples grown on MgO (100). In this case, x-ray diffraction showed that there was no twinning, and that the in-plane crystallographic domain size was ~28 nm.

Magnetization measurements were performed using a vibrating sample magnetometer (VSM). The external magnetic field was supplied by a 1.1 T electromagnet in the 15–300 K temperature range using a closed-cycle refrigerator. The VSM was only sensitive to the magnetization component parallel to the applied field. Figure 1 shows the measurement geometry. The samples were cooled in a field $H_{CF} = 2000$ Oe applied at an angle α with respect to the perpendicular bisector of the two AF crystallographic domains from a temperature of at least $T = 90$ K, which is greater than the T_N of the AF, to $T = 20$ K (the T_N of bulk $Fe_xZn_{1-x}F_2$ decreases linearly with x, from a maximum of 78.4 K for $x = 1.0$, for $x > 0.25$).[20] The cooling field was large enough to saturate the magnetization in the F layer during the cooling procedure. For the present samples, cooling in larger fields of up to 10 kOe did not alter the results below. Subsequently, magnetic hysteresis loops were measured at $T = 20$ K in the -5 kOe to $+5$ kOe field range. H_E was determined from the shift of the hysteresis loop from $H = 0$ with an accuracy of 5 Oe. By manually rotating the sample in the film plane, the loops were measured at different angles θ with respect to the perpendicular bisector for a given cooling field direction α. Both H_{CF} and H were applied in the film plane. The sample was then warmed up again to $T = 90$ K, rotated to a new angle α, and cooled again through T_N, and the procedure for measuring the hysteresis curves was repeated at $T = 20$ K. Hysteresis loops at $T = 300$ K and $T = 90$ K showed that the Co films deposited on top of the twinned AF layer did not

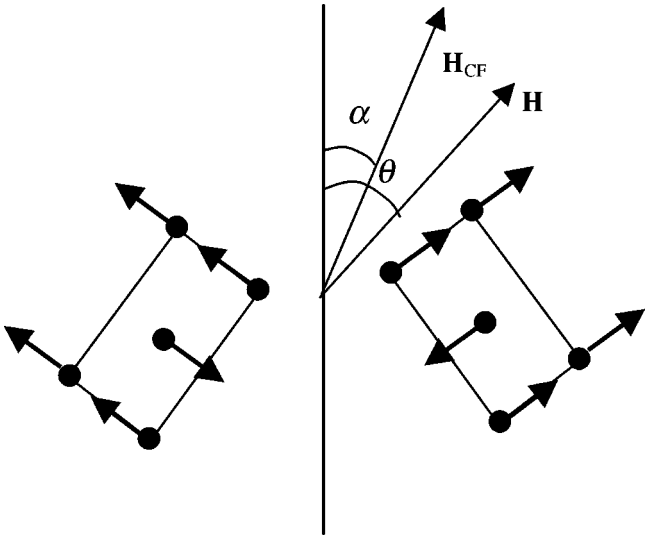

FIG. 1. Measurement geometry. The vertical line represents a perpendicular bisector of the two AF crystallographic domains. The low-temperature magnetic configuration of the Fe^{2+} ions is shown for reference. $\mathbf{H}_{CF}$ is the cooling field vector and **H** is the applied magnetic-field vector. α and θ are the angles between the bisector line and $\mathbf{H}_{CF}$ and **H**, respectively.

have an in-plane anisotropy above T_N. Co films grown on the untwinned AF did show a slight anisotropy at room temperature with an easy axis along the [001] direction.

III. RESULTS AND DISCUSSION

A. Twinned Samples

Figure 2 shows H_E, H_C, and M_R (normalized to the saturation magnetization M_S) as functions of θ for a FeF_2/Co bilayer and a $Fe_{0.84}Zn_{0.16}F_2$/FeF_2 (1.0 nm)/Co sample after being field-cooled along the $\alpha=0$ and $\alpha=45°$ directions. An

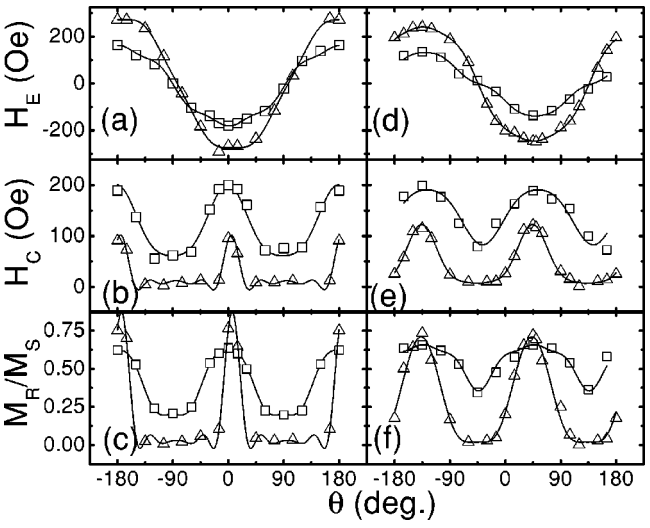

FIG. 2. H_E, H_C, and M_R/M_S as functions of θ for $\alpha=0$ (a–c) and $\alpha=45°$ (d–f), measured at $T=20$ K, for FeF_2/Co (□) and $Fe_{0.84}Zn_{0.16}F_2$/FeF_2 (1.0 nm)/Co (△) samples. Solid curves are fits to the Fourier components of Eq. (1).

enhancement of H_E occurs in the dilute sample, compared to the pure FeF_2/Co bilayer, when a 1.0-nm pure FeF_2 is deposited between the DAF and the F layer. Notice that H_E has 360° symmetry, while H_C and M_R have 180° symmetry. This is a result of the *unidirectional* nature of the exchange bias. For $\alpha=0$, the most negative value of H_E, $H_{E,\min}$, occurs at $\theta=0$, as expected for a cooling field that is small and positive.[21] Notice that the H_C maxima, M_R maxima, and the minima/maxima of H_E coincide perfectly. This result agrees with a single-particle model where a unidirectional anisotropy causes a significant shearing of M-H loops when the field is applied perpendicular to the anisotropy direction.[2] Interestingly, the peaks in H_C and M_R sharpen significantly as the Fe concentration x decreases. For $\alpha=45°$, H_{CF} points along the c-axis of one of the AF domains (see Fig. 1). In this case a shift of the H_E, H_C, and M_R maxima by 45° is clearly observed. In addition, the maxima of H_C and M_R are significantly broadened with respect to the $\alpha=0$ case, indicating the existence of a wider distribution of interface exchange anisotropies.

The solid curves in Fig. 2 are fits to the following equations:

$$H_E=\sum_{n=1}^{\infty} H_{En}\cos[(2n-1)(\theta-\phi)], \tag{1a}$$

$$H_C=\sum_{n=0}^{\infty} H_{Cn}\cos[2n(\theta-\phi)], \tag{1b}$$

$$M_R=\sum_{n=0}^{\infty} M_{Rn}\cos[2n(\theta-\phi)]. \tag{1c}$$

These equations represent a Fourier decomposition of H_E, H_C, and M_R, where ϕ is a phase difference with respect to $\theta=0$. This treatment is based on previous measurements of the angular dependence of these quantities, where it was shown that H_E can only have odd Fourier components and H_C and M_R must have even components.[3] The fitted coefficients for $H_E(\theta)$ are summarized in Table I. In this case it was sufficient to go to the $n=3$ term to reproduce the H_E data. Notice that the second-order term H_{E2} is only ~5% of the first-order term H_{E1}, which is negligible in this case. On the other hand, fitting H_C and M_R required higher-order terms comparable to the zeroth-order term, due to the sharply-peaked features shown in Fig. 2. The simple $\cos\theta$ dependence of H_E demonstrates that the exchange bias is strongly influenced by the uniaxial magnetic anisotropy in the AF layer, which leads to a strong interface interaction during the cooling procedure.

Further insight can be gained by plotting the angle (ϕ) where the minimum value of H_E occurs as a function of α, which coincides with H_C and M_R maxima, as shown in Fig. 3. Notice that ϕ remains unchanged at $\phi=0$ for $0°\leqslant\alpha\leqslant30°$, and then suddenly shifts to $\phi=90°$ in the $30°<\alpha<60°$ range for the samples without the pure AF interface layer. This is a clear indication that there are two stable domain structures that form as the sample is field cooled. Hence, when the sample is cooled within ±30° of one of the perpendicular

TABLE I. Summary of fitting parameters of H_E for $\alpha=0$ and $\alpha=45°$, respectively, for twinned samples. $C_n=H_{En}/H_{E0}$. The uncertainties are ± 2.5 Oe for H_{E0} and ± 0.025 for C_n.

	$\alpha=0$				$\alpha=45°$			
Sample	H_{E0} (Oe)	C_1	C_2	C_3	H_{E0}	C_1	C_2	C_3
FeF_2/Co	−171	1.00	−0.06	0.06	−126	1.00	0.12	−0.05
$Fe_{0.84}Zn_{0.16}F_2$/FeF_2(1.0 nm)/Co	−292	1.00	−0.03	−0.03	−258	1.00	−0.08	0.03
$Fe_{0.57}Zn_{0.43}F_2$/FeF_2(1.0 nm)/Co	−280	1.00	−0.04	−0.04	−242	1.00	−0.06	−0.03
$Fe_{0.62}Zn_{0.38}F_2$/Co	−111	1.00	−0.08	0.05	−73	1.00	−0.03	0.00
FeF_2/Co (untwinned)	−366	1.00	0.11	0.02				

bisectors, a stable AF structure forms such that the effective exchange anisotropy field $H_{E,\min}$ occurs in a direction along the perpendicular bisector. A more complicated structure is formed in the 30°–60° range, where a slight canting of the AF domains occurs. This provides evidence for the existence of an effective unidirectional anisotropy direction resulting from a frustration of the interface exchange interaction due to the small size of the AF structural domains (~6 nm–10 nm), which is much smaller than the lateral domain wall width of Co. The interface unidirectional anisotropy induced during the cool-down procedure is reversed in one of the domains in going from $\alpha=30°$ to $\alpha=60°$, causing the effective interface exchange field to rotate by 90°, as illustrated in Fig. 4.

Figure 3 also shows that the transition is substantially narrower for the case of samples having the interface pure AF layer, independent of the Fe concentration. This experimental result can be explained by assuming that the PAF/DAF short-range interface exchange interaction is significantly weaker than the PAF/F interaction. As the sample is cooled, the bulk of the AF orders more rapidly than the AF surface in contact with the F, in the same way that the surface of a ferromagnetic or antiferromagnetic material orders more slowly as the temperature is lowered below its critical temperature.[22] At low temperatures, the DAF tends to freeze along its anisotropy direction, whereas in samples without the PAF, the DAF will tend to make it easier to form domains that are not perfectly aligned along its easy direction. In other words, the PAF acts as a buffer between the F and the DAF, shielding the interaction between the DAF and the F layer, and causing the domains in the DAF layer to align more easily along the AF uniaxial anisotropy direction.

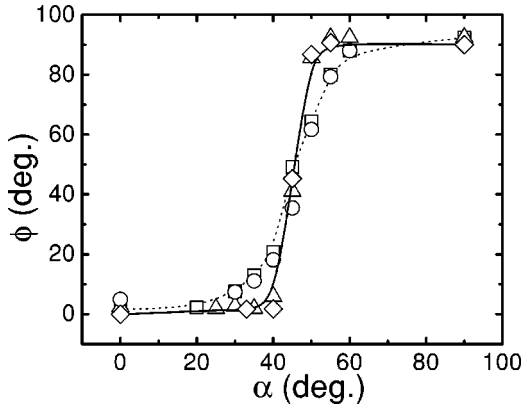

FIG. 3. Angular position ϕ of the H_E minima as a function of the cooling field direction α, measured at $T=20$ K for FeF_2/Co (□); $Fe_{0.62}Zn_{0.38}F_2$/Co (○); $Fe_{0.84}Zn_{0.16}F_2$/FeF_2 (1.0 nm)/Co (△); and $Fe_{0.57}Zn_{0.43}F_2$/FeF_2 (1.0 nm)/Co (◇).

The dependence of $H_{E,\min}$ as a function of α is shown in Fig. 5. In the $30°<\alpha<60°$ range the value of $|H_{E,\min}(\alpha)|$ abruptly dips to a value $\sim|H_{E,\min}(0)|/\sqrt{2}$, which occurs at $\alpha\sim45°$ for the pure sample. As previously noted,[23] in this configuration H_{CF} points parallel to one of the domains and perpendicular to the other. Since the coupling for each of the domains is perpendicular to the c axis, the exchange bias for the domain with its c axis parallel to H_{CF} is shut down during the cooling procedure, while the H_E for the other crystallographic domain is maximized. Assuming that the two crystallographic domains are on average identical in size, and that the maximum coupling to one of these domains is J_{eff}, the maximum value of $|H_{E,\min}|$ is proportional to twice $J_{\text{eff}}/\sqrt{2}$ for $\alpha=0$. On the other hand, for $\alpha=45°$, only one of the domains is active, so the maximum value of H_E is proportional to J_{eff}. We note that a significant disagreement with this expectation was recently observed in FeF_2/Fe bi-

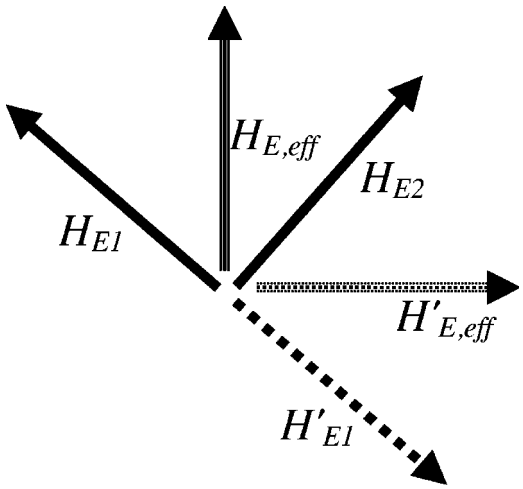

FIG. 4. Schematic for the effective exchange anisotropy fields generated during the field-cooling procedure. H_{E1} and H_{E2} are the exchange fields generated by the two perpendicular crystallographic domains when the sample is cooled along $\alpha=0$, and $H_{E,\text{eff}}$ is the effective exchange field detected by the F layer. When the sample is cooled with $60°\leqslant\alpha\leqslant90°$, one of the domains reverses its magnetic structure, resulting in an exchange field H'_{E1}, which causes the effective exchange field to rotate by 90° to $H'_{E,\text{eff}}$.

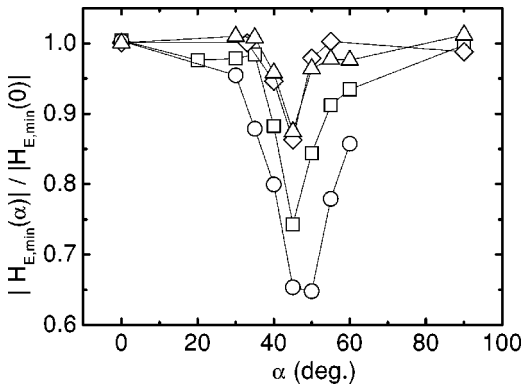

FIG. 5. Magnitude of the maximum value of $|H_E|$ as a function of α. Legend is as in Fig. 3.

layers, with $|H_{E,\min}(45°)|$ being a factor of 3 too small when the sample was cooled with H_{CF} applied at 45° from the bisector.[23] This discrepancy can be explained by a small misalignment of H_{CF} with the respect to the AF c axis, on the order of 5° or less, which could have caused the position of $H_{E,\min}$ to shift by approximately 20°–30°, yielding an apparently small value of $|H_E|$ measured along the cooling field direction. For the samples with the interface PAF layer in Fig. 5, the dip is less evident, perhaps due to the sharpness of the angular transition, so that the actual minimum is not really observed.

B. Untwinned Sample

In order to verify the exchange bias flop picture, the angular dependence of H_E was also measured in the untwinned AF sample grown as described above. Figure 6 shows that a large exchange bias is present if the sample is field-cooled from room temperature to 20 K in a field $H_{CF}=2000$ Oe parallel to the c axis of the AF layer, and then measured along c axis. However, no exchange bias is observed with H

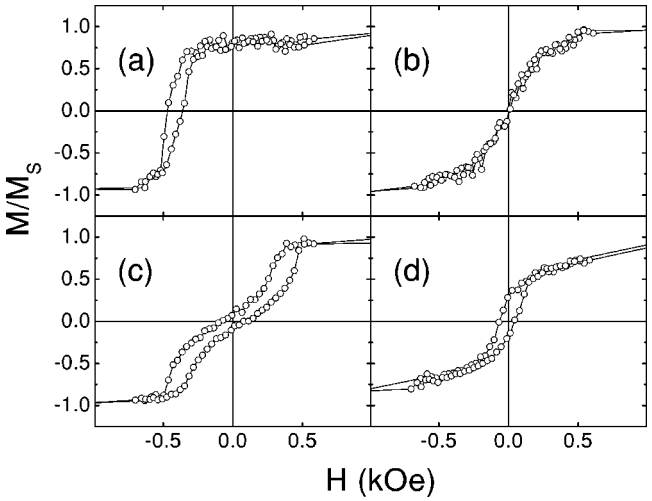

FIG. 6. Exchange bias in single-crystal FeF_2/Co bilayer with (a) $H_{CF}\|c$, $H\|c$; (b) $H_{CF}\|c$, $H\perp c$; (c) $H_{CF}\perp c$, $H\|c$; and (d) $H_{CF}\perp c$, $H\perp c$. Here c represents the direction of the FeF_2 c-axis. The data were obtained at $T=20$ K. Solid lines are guides to the eye.

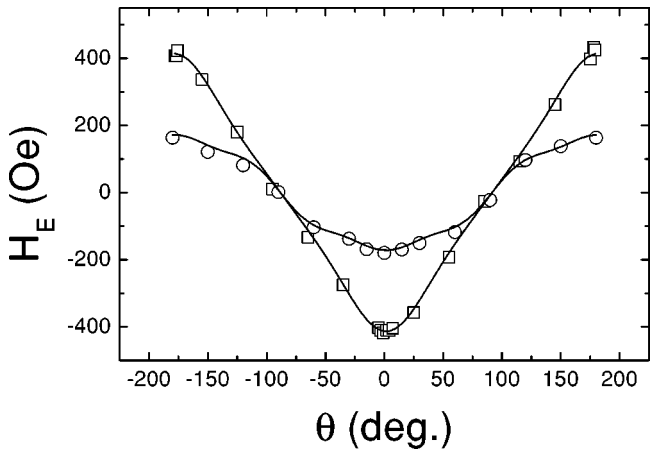

FIG. 7. Angular dependence of H_E for pure FeF_2 samples when cooled along the c axis of the FeF_2 for the twinned (○) and untwinned (□) samples. Solid curves are fits to Eq. (1a).

perpendicular to c axis, which implies that H_E in all AF domains is parallel to c axis ($H_E\|c$). Figure 6 also shows that after the sample is field cooled with $H_{CF}\perp c$, there is no net exchange bias with $H\|c$ or $H\perp c$. Nevertheless, a double loop is observed with $H\|c$, indicating that the local H_E vector direction in the AF layer can take one of two counterparallel directions. This is likely due to the formation of counterparallel domain states in the AF, where the sublattice magnetization in the two domains are counterparallel to each other, and the strong uniaxial anisotropy in FeF_2 does not permit the formation of significantly canted states at low temperatures.

The exchange bias angular dependence of the untwinned sample with $H_{CF}\|c$ is shown in Fig. 7. The angular dependence of the twinned sample is shown for comparison purposes, and the results of the fit to Eq. 1(a) are shown in Table I. Clearly the first-order $\cos\theta$ term still dominates, but the second-order term is now an appreciable 11% and positive, indicating that the interface coupling may not be entirely collinear.

Finally, the extreme sensitivity of the exchange bias to the cooling field direction is shown in Fig. 8. The figure demon-

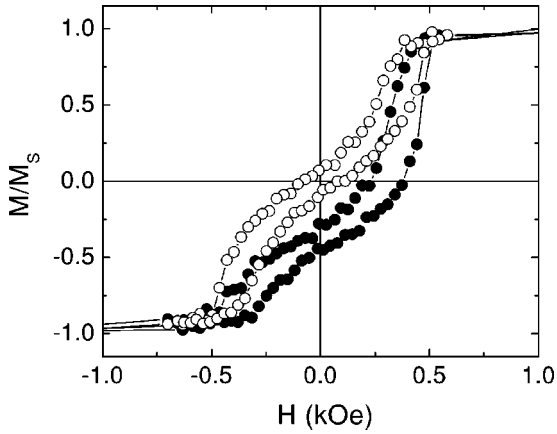

FIG. 8. Magnetic hysteresis loops measured with $H\|c$ in the untwinned FeF_2/Co bilayer after cooling with H_{CF} applied 90° to the c axis (○) and 91° to the c axis (●).

strates that cooling in a direction just 1° away from the direction perpendicular to the AF *c* axis results in a significant positive exchange bias of ~300 Oe. By assuming that the sample splits up into regions of positive and negative H_E, the data show that roughly 75% of the sample has a positive H_E due to the 1° misalignment. This remarkable angular sensitivity is reminiscent of the extreme sensitivity of the spin-flop transition in bulk MnF_2 to the applied field direction.[24] It is quite possible that the two effects have the same physical origin if the AF/F interface exchange interaction selects one of the two possible domain structures in the AF depending on the direction of the cooling field. In the bulk material, the domains would have the same energy, and the only way to make the sample single domain is to go through the spin-flop transition and then lower the field to zero. In the case of the exchange bias, the cooling field breaks the symmetry during the cooling procedure.

IV. CONCLUSIONS

In conclusion, we have shown that in $Fe_xZn_{1-x}F_2$/Co bilayers with AF having strong magnetic anisotropy, the domain structure in the AF formed during the cool-down procedure is very robust with respect to the cooling field angle. For most of the angular range, field cooling yields one of two equivalent antiferromagnetic domains in twinned AF samples. Only in a narrow angular range do different domain structures form, showing that the antiferromagnetic domain structure generated during the cool-down procedure can be much more robust than previously thought. A thin pure AF layer deposited at the dilute AF/F interface acts as a buffer which enhances the sharpness of the transition between different AF domain structures. For untwinned AF samples, H_E can only lie along the [001] in-plane *c* axis of the AF, independently of the cooling field direction. These results demonstrate that the interface exchange coupling responsible for H_E is extremely sensitive to the underlying magnetic anisotropy of the AF, and that the direction of the cooling field does not necessarily determine the direction of H_E.

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[1] For recent reviews of exchange anisotropy, see J. Nogués and I.K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999); A.E. Berkowitz and K. Takano, *ibid.* **200**, 552 (1999).

[2] W.H. Meiklejohn and C.P. Bean, Phys. Rev. **102**, 1413 (1956); **105**, 904 (1957).

[3] T. Ambrose, R.L. Sommer, and C.L. Chien, Phys. Rev. B **56**, 83 (1997).

[4] S.S.P. Parkin and V.S. Speriosu, in *Magnetic Properties of Low-Dimensional Systems II*, Vol. 50 of *Springer Proceedings in Physics*, edited by L.M. Falicov, F. Mejia-Lira, and J.L. Morán-López (Springer-Verlag, Berlin, 1990), p. 110.

[5] D. Lederman, J. Nogués, and I.K. Schuller, Phys. Rev. B **56**, 2332 (1997).

[6] H. Ohldag, T.J. Regan, J. Stohr, A. Scholl, F. Nolting, J. Luning, C. Stamm, S. Anders, and R.L. White, Phys. Rev. Lett. **87**, 247201 (2001).

[7] Y.J. Tang, B.F.P. Roos, T. Mewes, A.R. Frank, M. Rickart, M. Bauer, S.O. Demokritov, B. Hillebrands, X. Zhou, B.Q. Liang, X. Chen, and W.S. Zhan, Phys. Rev. B **62**, 8654 (2000).

[8] X.W. Wu, T. Ambrose, and C.L. Chien, Appl. Phys. Lett. **72**, 2176 (1998).

[9] T. Gredig, I.N. Krivorotov, C. Merton, A.M. Goldman, and E.D. Dahlberg, J. Appl. Phys. **87**, 6418 (2000).

[10] M.D. Stiles and R.D. McMichael, Phys. Rev. B **63**, 064405 (2001).

[11] For a recent review of exchange bias theory, see M. Kiwi, J. Magn. Magn. Mater. **234**, 584 (2001).

[12] A.P. Malozemoff, Phys. Rev. B **35**, 3679 (1987).

[13] U. Nowak, A. Misra, and K.D. Usadel, J. Appl. Phys. **89**, 7296 (2001).

[14] P. Miltényi, M. Gierlings, J. Keller, B. Beschoten, G. Güntherodt, U. Nowak, and K.D. Usadel, Phys. Rev. Lett. **84**, 4224 (2000).

[15] H. Shi, D. Lederman, and E.E. Fullerton, J. Appl. Phys. **91**, 7763 (2002).

[16] For a review of the RFIM, see D. Belanger and A.P. Young, J. Magn. Magn. Mater. **100**, 272 (1991).

[17] J. Nogués, D. Lederman, I.K. Schuller, and K.V. Rao, J. Appl. Phys. **79**, 5112 (1996).

[18] T.J. Moran, J. Nogués, D. Lederman, and I.K. Schuller, Appl. Phys. Lett. **72**, 617 (1998).

[19] J. McChesney, M. Hetzer, H. Shi, T. Charlton, and D. Lederman, J. Mater. Res. **17**, 1769 (2001).

[20] G.K. Wertheim, D.N.E. Buchanan, and H.J. Guggenheim, Phys. Rev. **152**, 527 (1966).

[21] H_E can be positive in FeF_2 (110)/Fe bilayers for large positive cooling fields, presumably due to antiferromagnetic exchange coupling at the AF/F interface. See J. Nogués, D. Lederman, T.J. Moran, and I.K. Schuller, Phys. Rev. Lett. **76**, 4624 (1996).

[22] S. Alvarado, M. Campagna, and H. Hopster, Phys. Rev. Lett. **48**, 51 (1981).

[23] M.R. Fitzsimmons, C. Leighton, J. Nogués, A. Hoffmann, K. Liu, C.F. Majkrzak, J.A. Dura, J.R. Groves, R.W. Springer, P.N. Arendt, V. Leiner, H. Lauter, and I.K. Schuller, Phys. Rev. B **65**, 134436 (2002).

[24] G.P. Felcher and R. Kleb, Europhys. Lett. **36**, 455 (1996).