Spin Structure at the Interface of Exchange Biased FeMn/Co Bilayers

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The origin of exchange biasing in FeMn/Co bilayers is elucidated using magneto-optic Kerr effect and x-ray dichroism. It is found that the FeMn spin structure is aligned with the ferromagnetic (FM) moment of the Co layer, indicating that "spin flop" coupling is *not* the mechanism for exchange bias in this system. Futhermore, the Fe forms an uncompensated surface. It is likely that the FM Fe spins play a key role in the generation of the exchange bias. These results provide new insight to the mechanism of exchange biasing in metallic ferromagnetic/antiferromagnetic systems.

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Although Meiklejohn and Bean [1] discovered the exchange bias phenomenon more than 40 years ago, it is still not well understood. This "locking" of the magnetization direction of a ferromagnetic (FM) layer in contact with an antiferromagnetic (AF) layer manifests as a shift of the hysteresis loop by a bias field H_b. The earliest theory explained the effect in terms of an uncompensated monolayer of spins at the surface of the antiferromagnetic layer [2]. However, this model overestimates the observed H_b by a factor of 100 [3].

In recent years, interest in exchange biasing has intensified due to its usefulness in magnetoresistive sensors. Several recent theories give improved predictions of the size of H_b, but do not agree on the physical explanation of the effect. Malozemoff proposed a model with random exchange interactions at the AF/FM interface. These random interactions, due to surface roughness, lead to the formation of domains at the interface and give rise to a smaller H_b [3]. Mauri *et al.* proposed a subsequent model with the formation of a domain wall in the AF which also reduces H_b [4]. Finally, Koon performed calculations indicating 90° or "spin flop" coupling between the AF and FM layer, which correctly predicted the magnitude of H_b [5]. However, the sign of the bias was not definitely determined. This was recently addressed by Hong [6]. Note that spin flop coupling can occur only for antiferromagnetic layers with an alternating 180° spin structure.

Recently Takano *et al.* performed direct measurements of uncompensated spins at the surface in CoO layers in CoO/MgO and CoO/Py (Py = $Ni_{81}Fe_{19}$) superlattices [7]. They found approximately 1% of one monolayer (ML) of Co surface spins were uncompensated, and showed evidence that these spins lead to exchange biasing when CoO is used in FM/AF bilayers (supporting Malozemoff's model). In contrast to this, Ijiri *et al.* used neutron diffraction and found spin flop coupling within Fe_3O_4/CoO superlattices [8], in support of Koon's model. Another experiment, examining Fe/FeF_2 bilayers, discovered a positive exchange bias [9] and spin flop coupling [10], both of which are explained within Koon's model [5,6]. Hence the experimental evidence for the origin of exchange bias is not conclusive.

Furthermore, note that, in the experimental work cited above, the AF layers are all insulating and have a bulk spin structure consisting of alternating layers of spins with 180° alignment. This is not the case with FeMn and other metallic AF layers that are commonly used in magnetoresistive sensors. For example, FeMn has a randomly occupied fcc lattice with a noncollinear (possibly tetrahedral) spin structure [11]. In this arrangement spin flop coupling cannot occur, which would appear to rule out Koon's model. However, it is not known how the FM layer affects the spin structure within the AF layer so this conclusion is premature. Here we use x-ray magnetic circular dichroism (XMCD) and x-ray magnetic linear dichroism (XMLD) to study the spin structure of both the FM and AF layers within Co/FeMn bilayers, which serve as a prototype for other systems with metallic AF layers.

Samples were prepared using magnetron sputter deposition on Si(001) at room temperature. The deposition system has a base pressure of 5×10^{-10} Torr and a 3.25×10^{-3} Torr Ar atmosphere during deposition. The samples were grown in the presence of a 500 G magnetic field generated by a permanent magnet backing the substrate. This field serves to "set" the bias field direction of the ferromagnetic layer. This report focuses on three samples, the first incorporating a FeMn "wedge" with the following structure: 50 Å Ta/20 Å Py/0–100 Å FeMn/17 Å Co/14 Å Al. The Ta and Py layers are present to ensure that the γ phase of FeMn is obtained, while the Al layer is used to prevent oxidation [12]. The second sample is similar but has a fixed FeMn thickness, with structure: 50 Å Ta/20 Å Py/70 Å FeMn/11 Å Co/14 Å Al. The final sample used a Co wedge: 50 Å Ta/20 Å Py/70 Å FeMn/0–15 Å Co/14 Å Al.

The samples were studied using magneto-optic Kerr effect (MOKE) loops. The upper inset of Fig. 1 is a hysteresis loop for a FeMn thickness t_{FeMn} of 70 Å along the FeMn wedge. MOKE has a sampling depth of ≈200 Å, thus it is possible to see both the Py underlayer and the Co overlayer. Py, with a smaller magnetization

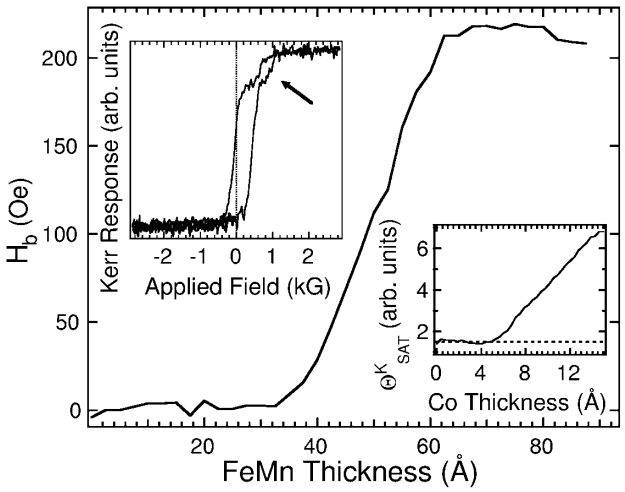

FIG. 1. Plot of Co H_b vs t_{FeMn}. These values are extracted from MOKE hysteresis loops. The upper inset is a hysteresis loop for $t_{\mathrm{FeMn}} \approx 70$ Å. The lower inset shows Θ_K^{sat} as measured from the Co wedge film, indicating that 2–3 ML of Co are ferromagnetically "dead."

and a signal further reduced by attenuation, is seen in the top part of the hysteresis loop (marked with an arrow). The larger, bottom part of the loop is due to the Co overlayer. From loops such as these, values of H_b are extracted for both the Co and the Py.

Concentrating on the Co, a plot of H_b vs t_{FeMn} is shown in Fig. 1. The bias begins to have an effect when $t_{\mathrm{FeMn}} \approx$ 30 Å, and saturates at $t_{\mathrm{FeMn}} \approx 60$ Å. This is due to finite size effects. Layers of FeMn thinner than ≈30 Å have a blocking temperature below room temperature. As t_{FeMn} increases, the blocking temperature increases also. The coercivity (not shown) shows a sharp rise coinciding with the bias turning on. With increasing t_{FeMn} the coercivity value decreases slightly. The coercivity at $t_{\mathrm{FeMn}} = 70$ Å is 250 Oe. The behavior of the coercivity is consistent with that seen previously in a FeMn/Py bilayer system [13].

The interfacial spin structure is determined using XMCD [14] and XMLD [15,16] performed at the Synchrotron Radiation Center (University of Wisconsin). In XMCD, 85% circularly polarized x rays are incident at an angle of 45° with respect to the surface normal. Two x-ray absorption spectra are taken concurrently by measuring the total electron yield (TEY). For the first, the sample is magnetized such that the projection of the magnetization **M** is parallel to the photon helicity. The magnetization is then switched 180° and a point in the second spectrum is recorded. The difference between the two spectra is the XMCD which is proportional to the average magnetic moment per atom $\langle \mu_i \rangle$ (i = Mn, Fe, Co). This lets us characterize ferromagnetism within the Co and near the FeMn interface, but the relatively short probing depth of TEY eliminates any contribution from the Py layer.

In a perfect AF the XMCD is zero. Thus to characterize the FeMn layer we employ XMLD. XMLD uses normally incident linearly polarized light and switches **M** in 90° steps between parallel and perpendicular to the polarization axis. Sequential measurements at 0°, 90°, 180°, and 270° are taken at each photon energy. The 0° and 180° are averaged to give $\alpha_{\parallel}$, while the 90° and 270° measurements are averaged to give $\alpha_{\perp}$. The difference spectrum ($\alpha_{\perp} - \alpha_{\parallel}$) gives a measure of $\langle \mu_i^2 \rangle$. Note that XMLD gives a maximal signal when the sublattice of a given element has a collinear spin arrangement (e.g., FM or 180° AF), but gives zero signal for many AF spin structures including that of bulk FeMn [11].

In most FM samples flipping the magnetization by 180° using an applied field is equivalent to rotating the sample by 180° in zero applied field. But in exchange biased samples the former experiment leads to the formation of a domain wall parallel to the sample surface, whereas the latter does not. To probe the difference between these two states a second set of XMCD (and XMLD) measurements were made by mounting the sample on a computer-controlled motorized rotary feed through. The XMCD spectra were obtained by rotating the sample normal back and forth between +45° and −45° (with regard to the photon helicity) at each photon energy. Similarly, XMLD data were collected using linearly polarized x rays and rotating the sample about the surface normal in 90° steps. To distinguish them, data taken while rotating the sample are given the subscript R, while data taken with an external magnetic field are subscripted H.

The XMCD spectra of the 70 Å FeMn/11 Å Co sample are shown in Fig. 2. The data are for the L absorption edge of each of the three elements. For the XMCD$_H$ (and XMLD$_H$) measurements, a static field was applied to cancel the effect of H_b. Then a dynamic field flipped the magnetization symmetrically about this compensated state. A method has been developed to normalize and then compare XMCD [17,18] to "standard" spectra taken from samples with a known moment. In this way we obtain quantitative measure of the average moment per atom within the sample. However, not all atoms carry a moment. To count spins it is necessary to assume a given value of the moment within those atoms that contribute to the dichroism signal. Here we assume the Fe has a moment close to $2\mu_B$ since this is the case for many FeCo and FeMn alloys. Likewise, we assume Co atoms have their bulk moment ($1.6\mu_B$) for the discussion below. These choices are necessarily rough estimates, and any error in our choice is propagated into our estimates of magnetic thicknesses below.

In Fig. 2, observe the lack of a Mn XMCD$_H$ signal. A similar spectrum was observed for XMCD$_R$. This indicates that the Mn spins are almost perfectly compensated with no more than a few percent of 1 ML residual ferromagnetic spins.

One might expect a similar result for the Fe. However, substantial Fe XMCD$_H$ is observed amounting to 4.1 ± 0.4% of that from a thick Fe standard. Using

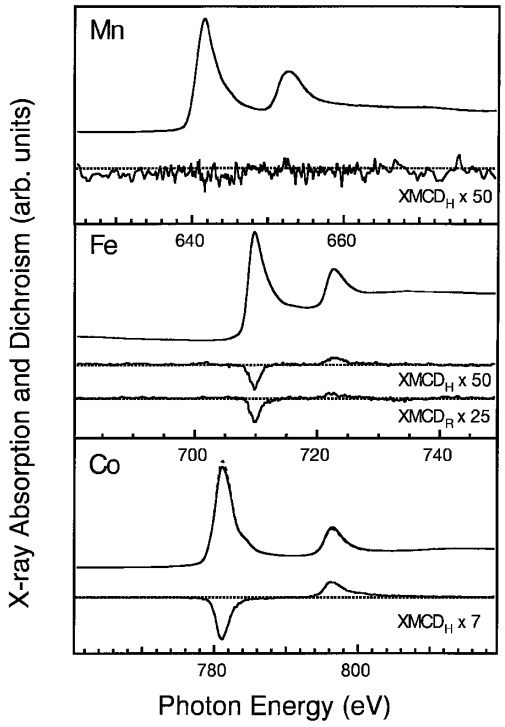

FIG. 2. X-ray absorption and circular dichroism vs photon energy at the L edge of Mn, Fe, and Co. The Mn and Co spectra were taken by flipping the magnetization in the Co layer (i.e., XMCD$_H$). For Fe, both XMCD$_H$ and XMCD$_R$ are shown.

$\langle \mu_{\mathrm{Fe}} \rangle \approx 2\mu_B$, we estimate about 0.4 of one fcc(111) ML of Fe spins flip with (and are parallel to) the Co [19]. These Fe atoms are effectively part of the FM layer. Interestingly, the Fe XMCD$_R$ signal is twice as large. Thus the surface of the AF layer has about 0.8 ML of uncompensated Fe spins aligned with the Co in the remanent state, but only half of which switch with the Co.

Finally, the Co shows substantial XMCD$_H$ as anticipated. Yet the measured XMCD$_H$ is only one-fourth as large as a thick Co standard. With the assumed Co moment, this indicates a net "loss" of 2–3 ML of Co spins. Since this film was capped [20] we conclude that the lost spins are at the Co/FeMn interface. To verify the number of lost spins, MOKE loops were acquired from the Co wedge film and the saturation Kerr effect Θ_K^{sat} is plotted in the lower inset of Fig. 1. It is seen that Θ_K^{sat} rises linearly from the Py base-line level beginning at $t_{\mathrm{Co}} = 5$ Å, in excellent agreement with the XMCD result. We hypothesize that these Co atoms have interdiffused with the FeMn layer and are participating in the AF state. This is perhaps not surprising since CoMn alloys are antiferromagnetic even for Mn concentrations down to 35%. The Co XMCD$_R$ is not significantly different from the XMCD$_H$.

To characterize the AF state within the FeMn layer the XMLD spectra for Mn and Fe were collected [21]. Not surprisingly, XMLD$_H$ from both Fe and Mn showed a negligible signal. This indicates that the AF spins are bound to one orientation and are not free to rotate with the Co layer, just as is usually assumed for exchange biased systems.

Comparatively, clear Fe and Mn XMLD$_R$ signals are observed (Fig. 3). Recall that in ferromagnetic transition metals XMLD is typically 10 times smaller than XMCD [16]. Thus, the Fe XMLD$_R$ in Fig. 3 is much too large to be accounted for by those few uncompensated Fe spins which give XMCD in Fig. 2. This indicates a considerable signal from Fe atoms in the AF layer. Likewise, Mn showed zero XMCD$_R$, so all of the Mn XMLD$_R$ signal must originate from within the AF layer.

The presence of XMLD$_R$ indicates that the AF spin structure near the Co/FeMn interface is not the same as that of bulk FeMn. The XMLD spectrum of a bulk Fe sample [16] is shown in Fig. 3 (top XMLD spectrum). By comparing the shape of the Fe XMLD$_R$ with that of the bulk Fe we determine that the unique spin axis within the AF Fe is *parallel* to the exchange bias of the Co film. This definitively rules out spin flop coupling in the present system since a 90° orientation of the Fe spin axis would invert the Fe XMLD spectrum, and this is not observed.

No suitable calibration spectrum for Mn XMLD was available. However, the Mn XMLD$_R$ is similar in magnitude to that from the Fe, suggesting that roughly the same number of Mn spins contribute to the signal as in the Fe case. Furthermore, the similarity in the absorption line shapes suggests that the Mn spin axis is parallel to that of the Fe.

It has been theorized [5] and seen experimentally in the Fe_3O_4/CoO system [8] that the AF layer moments can align perpendicular to the FM layer. The XMLD$_R$ data indicate that this is not the case with the FeMn/Co system. Here we observe a net ferromagnetic moment

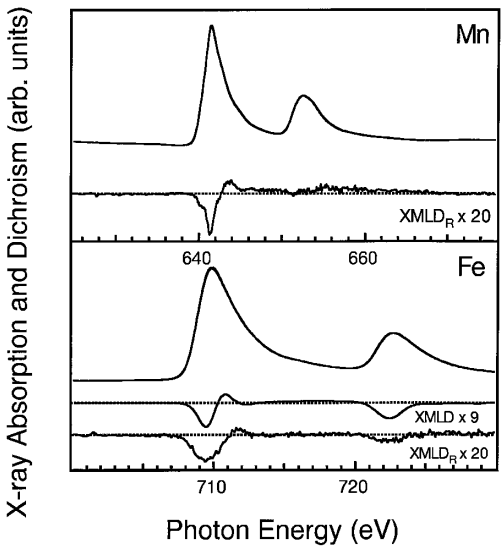

FIG. 3. X-ray absorption and linear dichroism vs photon energy at the L edge of Mn and Fe. For Fe, the top XMLD spectrum is that of a thick Fe standard, while the bottom spectrum is from the exchange biased sample.

in the Fe spins amounting to almost one ML of atoms. Only half of these atoms "belong" to the FM layer while the other half are strongly coupled to the AF layer. The coupling between Fe atoms on either side of the interface may be the cause of exchange biasing in this system (i.e., Malozemoff's model applies). Co atoms near the interface might play the same role, but such a small change in the relatively large Co XMCD signal was below our sensitivity limits.

Also keep in mind that in the interface region, 2–3 ML of Co atoms appear to participate in the AF layer. This, and the presence of the nearby FM Co layer, may explain the deviation of the top few ML of the AF layer from the bulk FeMn spin structure. Moreover, it is known that AF CoMn alloys have a 180° spin structure [11] which supports this interpretation. It seems likely that the unique spin axis of the AF layer is important to the mechanism of exchange biasing in the present system. A similar mechanism might also be at work at the Py/FeMn interface since NiMn alloys are also known to have a 180° spin structure [11].

Finally, the determination of the FeMn spin structure using the above measurements can be summarized by reiterating the two most important results. First, the FeMn spin axis is aligned *parallel* to the ferromagnetic Co moments. Thus the spin flop mechanism is *not* relevant to this system. Second, the Fe is found to form an uncompensated surface. The ferromagnetic Fe spins, which are divided evenly between the FM and AF layers, probably play a key role in the generation of the exchange bias.

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[19] The thickness of the magnetic layer t_M is calculated from $C\int_0^\infty \exp(-\tau/\lambda)\,d\tau = \int_0^{t_M} \exp(-\tau/\lambda)\,d\tau$, where C is the ratio of the measured XMCD signal to that of the bulk. $\lambda = 20$ Å is the sampling depth of the TEY measurement.
[20] We have previously tested Al capping layers and have never found any suppression of magnetic moments associated with them, for either Fe or Co.
[21] The XMLD spectra from the Co showed measurable signals but their interpretation is difficult, because the FM component of the Co is incompletely magnetized during the XMLD_R measurement. In the XMCD it is possible to correct for this using MOKE loops, but since the XMLD contains contributions from both FM and AF Co, making such a correction is impossible.