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Onset of exchange bias in ultrathin antiferromagnetic layers

M. Ali,* C. H. Marrows, and B. J. Hickey
Department of Physics and Astronomy, E. C. Stoner Laboratory, University of Leeds, Leeds LS2 9JT, United Kingdom

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Current theoretical explanations of exchange biasing are based upon magnetic domains in the antiferromagnetic layer being responsible for the phenomenon. Both the ideas of planar and perpendicular domain walls have been developed in explaining the various observed effects. Here the exchange bias (H_{ex}) has been investigated as a function of the antiferromagnetic (AF) layer thickness (t_{AF}) in IrMn/Co and FeMn/Co exchange biased systems. The results indicate that the onset of biasing occurs for t_{AF} which appears to be far too low (~ 10 Å) to accommodate planar domain walls (~ 200 Å) within the AF layer. From these results it is inferred that planar domain walls cannot therefore be responsible for biasing, and that theoretical calculations involving perpendicular domain walls in the antiferromagnetic layers appear to be the more plausible explanation.

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The interfacial exchange coupling that exists between the spins of a ferromagnet (F) and an antiferromagnet (AF) has been extensively studied in recent years. The two 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_{ex}), and its associated coercivity enhancement (H_c). Despite the fact that exchange biasing was discovered over 45 years ago, a full microscopic description is still being sought. It is generally accepted that exchange coupling is related to the details of the actual spin arrangement at the F/AF interface. The mechanism controlling the final spin structure at the interface is an issue that still needs to be resolved.

The original interpretation by Meiklejohn and Bean[1] assumed that H_{ex} was a consequence of the competing Zeeman and exchange-coupling energies across an ideal, smooth, magnetically (AF) uncompensated interface with rigid spins. However, this simple picture predicted values for H_{ex} that were roughly two orders of magnitude too large when compared to experimental values. Moreover, such ideal interfaces are unlikely to occur in real samples.

In an attempt to resolve this discrepancy a number of theories have been developed that have yielded values for H_{ex} in agreement with experiment. Theoretical models have considered both compensated and uncompensated interfaces,[2–6] single-crystal and polycrystalline systems,[2,7,8] spin-flop coupling,[5] interface roughness,[4,9] and magnetic domains in the antiferromagnetic layer.[2–4,11,10] The most promising models have been in this final group: those involving magnetic domains in the AF. Mauri *et al.* developed a model using the idea, first introduced by Néel,[12,13] of planar domain walls originating at a smooth AF interface, where the AF spins rotate in the plane.[3] This allows the exchange energy to be spread across the width of a domain wall in contrast to two atomic sites at the interface, reducing H_{ex}. However, Malozemoff argued that an ideal interface was unrealistic and structural roughness would lead to magnetic defects giving rise to local random fields.[4] In order to minimize the energy of the system, it was shown that by allowing the AF to break up into domains, where the domain walls are now perpendicular to the interface, the energy of the system including that from the local random fields is minimized, and realistic values for H_{ex} are obtained.

Element specific imaging by photoelectron emission microscopy, in conjunction with x-ray magnetic circular dichroism, of epitaxially grown[15] Co/LaFeO$_3$ and Co/FeMn (Ref. 16) systems has highlighted the existence of magnetic domains in the AF. Similar measurements carried out on polycrystalline samples of Co/IrMn and Co/FeMn biased systems[17] have also shown the existence of domains in the AF layer. It was found that the domain structures in both the F and AF layers were always extremely highly correlated. A complex random domain structure was found to form in the F layer during reversal of its magnetization. Neutron reflectometry studies on Co/FeMn superlattices[18] have also shown complex domain structures present in the Co layers on reversal. Measurements carried out on Fe$_3$O$_4$/NiO superlattices[19] have shown that in the presence of exchange biasing the formation of both parallel and perpendicular domain walls occur in the AF as the sample is allowed to cool through the blocking temperature (T_B). Further evidence of domain structures in the AF controlling biasing was highlighted by Miltényi *et al.*[20] where impurities were introduced into the AF layer to form and influence domains which in turn affected the biasing.

Models with planar or perpendicular walls in the AF layer make different predictions for the dependence of H_{ex} on AF layer thickness, t_{AF}. The majority of experimental work on biasing as a function of t_{AF} has focused on temperatures at or above room temperature for technological reasons. Results so far have often been interpreted in terms of parallel domain walls in the AF.[14,23] In this paper, we will show that biasing can occur where the AF layer is far too thin to support such a parallel wall.

The IrMn/Co and FeMn/Co specimens used in this study were prepared by dc magnetron sputtering at an argon working pressure of 2.5 mTorr as part of a spin-valve structure. Each set of specimens consisted of 15 samples which were grown during the same vacuum cycle. The base pressure prior to the deposition was of the order of 2×10^{-8} Torr. The free Co layer within the spin-valve structure was used as a control layer during the measurements. The spin-

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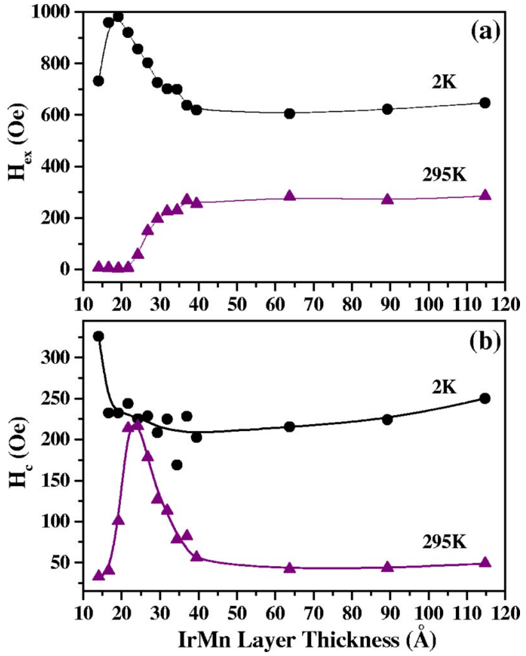

FIG. 1. IrMn layer thickness dependance of the exchange bias field H_{ex} and coercivity H_c. The circular symbols represent measurements taken at 2 K whereas the triangular symbols were taken at 295 K. The solid lines are guides to the eye.

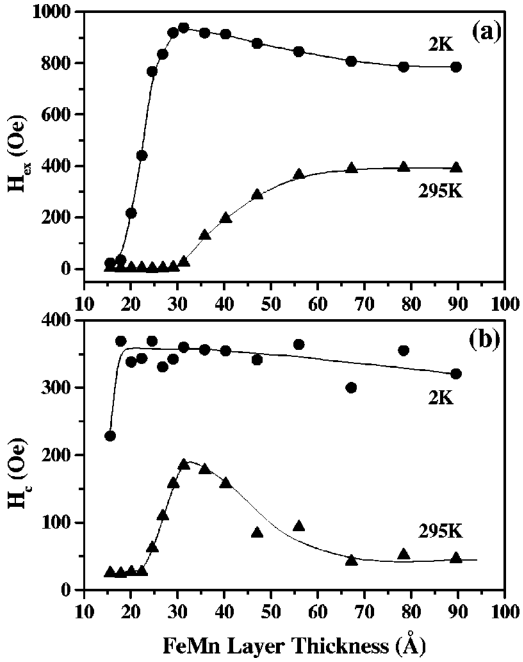

FIG. 2. FeMn layer thickness dependance of the exchange bias field H_{ex} and coercivity H_c. The circular symbols represent measurements taken at 2 K whereas the triangular symbols were taken at 295 K. The solid lines are guides to the eye.

valve structures Ta(75 Å)/Co(40 Å)/Cu(23 Å)/Co(26 Å)/IrMn(t_{AF})/Ta(25 Å) and Ta(75 Å)/Co(33 Å)/Cu(23 Å)/Co(22 Å)/FeMn(t_{AF})/Ta(25 Å) were deposited onto silicon (100) substrates in a forming field of 200 Oe at room temperature. The tantalum buffer promotes a preferential (111) texture. Layer thicknesses were confirmed by grazing incidence x-ray reflectivity. Magnetometery measurements were done using vibrating sample magnetometery (VSM) from 2 K upwards.

Figure 1(a) presents the exchange bias field values as a function of the IrMn layer thickness. The trend obtained at 295 K is typical of those which are generally found in most systems.[11,21,22] In this case the onset of biasing appears at $\approx$20Å, and it is fully established at around 40 Å where it saturates. However, it has been reported in some instances that H_{ex} decreases slowly above the critical thickness,[23] and the cause of this is either a reduction in the AF domain or grain size. No such behavior was seen in either of the systems studied here at room temperature (295 K). However at 2 K, the onset of biasing appears at $\sim$10 Å and peaks at 20 Å and then falls to its saturation value above a thickness of 40 Å and strongly resembles the predictions of the Malozemoff[4] model that involves perpendicular domain walls. However, this is a 0 K theory, and it is clear that temperature has a significant effect on these measurements, since at 295 K there is no biasing at 20 Å, whereas at 2 K H_{ex} is of the order of 1000 Oe. For temperatures in between it is found that after H_{ex} peaks there is a slow decrease before leveling off at 40 Å. The data at 295 K have thus far been interpreted in terms of planar (Mauri) domain walls.[11] The AF layer thickness at which H_{ex} appears is said to be the point at which the AF layer is able to accommodate a planar domain wall. At this t_{AF} there is also a peak in H_c, which we attribute to the formation of the AF domain structure which is reversible until the anisotropy is sufficient to stabilize the AF domain structure. It should be noted that the coercive field of the unpinned Co layer at 2 K is $\sim$50 Oe, and only $\sim$20 Oe at 295 K. The coercive field at the two respective temperatures remains constant as function of t_{AF} as one would expect. Similar data are also shown for the FeMn/Co system in Fig. 2. For the FeMn system the onset of biasing occurs at 30 Å at 295 K and reaches its saturated value at some 80 Å. At 2 K biasing appears at $\sim$15 Å and peaks at 30 Å (H_{ex}=900 Oe) before falling to a constant value. It can be inferred from both the onset of biasing and the critical thickness that the IrMn system has a higher anisotropy (K_{AF}) than the FeMn. The lower critical thickness for IrMn at 295 K indicates that the volume anisotropy is much larger and hence provides a larger thermal stability for the AF domain structure. Again the FeMn/Co system shows similar trends to the data of the IrMn/Co. The peak in H_{ex} is less intense at 2 K, but one would expect this to be the case because of the lower K_{AF}.

The stability of both H_{ex} and H_c over repeated hysteresis loop measurements performed at 2 K is shown in Fig. 3 for an IrMn layer thickness of 14 Å, the thinnest we investigated. It was found that the free Co layer exhibited no training effects. Even for this extremely thin AF layer, it is clear that exchange biasing does persist despite taking account of the effects of training. It can be seen that the biasing becomes relatively stable after only two cycles, and the magnitude of H_{ex} decreases by some 20% to a stable value of 730 Oe as shown in Fig. 3(b). One also finds that the coercive field also decreases accordingly with H_{ex}. The training

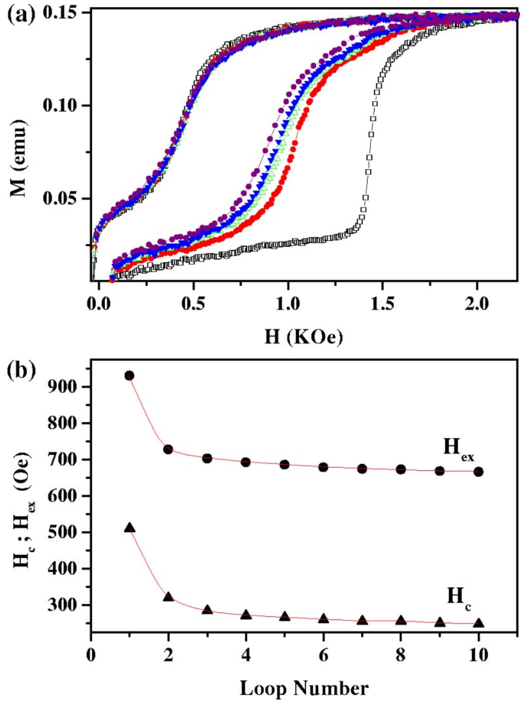

FIG. 3. The magnetic training effect exhibited at 2 K by a Co layer exchange biased to a IrMn layer thickness of 14 Å within a spin-valve structure. Field cooled from 295 K in 0.4 T. (a) Ten repeated VSM loops indicating the magnetic training effect in the pinned Co layer. For clarity only loops 1, 2, 3, 4, and 10 are shown in the figure for the biased layer. (b) H_{ex} and H_{c} as a function of repeated loop number—the lines are a guide to the eye.

effect is only observable on the right-hand side of the hysteresis loop and the left-hand side of the loop remains static. The training effect exhibited by the right-hand side of the loop can be easily understood by the reorientation of the AF domain structure, either through the consequence of domain-wall motion or spin rotation. The sample in this instance was cooled in a negative field of 4 kOe, which ensures that the Co layer is saturated. As the temperature falls below T_B, the AF domain structure which develops is solely influenced by the single Co domain. With no thermal assistance available for the AF domain structure to minimize itself into its lowest possible energy state, taking account of all energies present, it remains in a metastable state. Only on application of a positive field is there sufficient energy provided for AF domains to reorientate themselves leading to the training effect as the Co layer switches.[4,24] It would seem that the main mechanism at work is domain-wall motion if one assumes that the enhanced coercivity is a result of the F domains being pinned at the AF domain walls—fewer AF domain walls lower H_{c}. It is clear that the values of H_{ex} and H_{c} settle to a constant value after only a few loops, and it is this value that we plot in Figs. 1 and 2. It was found that the magnitude of the training diminished rapidly with increasing AF thickness (i.e., ~1% at 20 Å). The training on one side of the loop is similar to that predicted by Fujiwara *et al.*[25]

Using the expression

$$\delta_{\mathrm{W}} = \frac{\pi}{2}\sqrt{\frac{A_{\mathrm{AF}}}{K_{\mathrm{AF}}}} \tag{1}$$

for the domain-wall width δ_{W} in a fcc structure, where K_{AF} is the anisotropy constant and A_{AF} is the exchange stiffness, one can calculate a typical domain-wall width in an AF for comparison. Typical values for K_{AF} for IrMn and FeMn are 1.8×10^5 J/m^3 (Ref. 26) and 1.3×10^4 J/m^3 (Refs. 3 and 27), respectively. Experimental values for the exchange energy are more problematic, but one can obtain approximate values based on the bulk Néel temperatures of these materials using the expression[28]

$$A_{\mathrm{AF}} = \frac{3k_B T_N}{aZ}, \tag{2}$$

where Z is the number of nearest neighbors, a is the lattice parameter, and k_{B} is the Boltzmann constant. Using values of 500 K (IrMn) and 430 K (FeMn) for T_{N}, one obtains [$Z=12$,$a=3.82$ Å (IrMn),$a=3.63$ Å (FeMn)]4.5×10^{-12} J/m and 4.1×10^{-12} J/m, respectively, for A_{AF} which compares well with other calculated[3,27] values. From these values domain-wall widths of 80 Å for IrMn and 280 Å for the FeMn are obtained. These calculated values clearly show that a planar domain wall therefore cannot form in such thin AF layers and suggests that they cannot be responsible for biasing. One might argue that the onset of H_{ex} is the point at which there is sufficient material for the layer to behave like an AF. However, from Figs. 1(b) and 2(b), it can be seen that there is enhancement in H_{c} before the appearance of any biasing. This indicates that the layer is already behaving as an AF. Work by van der Zaag *et al.* on epitaxially grown Fe3O/CoO has shown the presence of biasing with CoO AF layers as thin as 4 Å.[29]

To summarize, we have shown that stable exchange biasing is present in the IrMn/Co ($t_{\mathrm{AF}}\sim10$ Å) and FeMn/Co ($t_{\mathrm{AF}}\sim15$ Å) systems, where the AF layers are far too thin to accommodate planar domain walls as suggested by the Mauri-type models. Even for these small t_{AF} values it has has been demonstrated that H_{ex} is substantial and stable over repeated reversals of the Co layer. The overall shape of $H_{\mathrm{ex}}(t_{\mathrm{AF}})$ is also difficult to explain within this picture. However, domain models proposing perpendicular walls have no such predicament, since these types of walls are not limited by the thickness of the AF layer.

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*Email address: phyma@phys-irc.leeds.ac.uk; URL: http://www.stoner.leeds.ac.uk

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