Controlled enhancement or suppression of exchange biasing using impurity δ layers

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The effects of inserting impurity δ layers of various elements into a Co/IrMn exchange biased bilayer, both at the interface and at given points within the IrMn layer a distance from the interface, have been investigated. Depending on the chemical species of impurity, and its position, we found that the exchange biasing can be either strongly enhanced or suppressed. We show that biasing is enhanced with a dusting of certain magnetic impurities, present either at the interface or sufficiently far away from the Co/IrMn interface. This illustrates that the final spin structure at the Co/IrMn interface is not only governed by interface structure and/or roughness, but is also mediated by local exchange or anisotropy variations within the bulk of the IrMn.

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I. INTRODUCTION

The fascination with understanding exchange bias has shown no noticeable change, considering that 50 years have elapsed since its discovery by Meiklejohn and Bean.[1] This impetus is both practical and fundamental,[2] since the effect both forms the integral component of devices such as spin valves, magnetic tunnel junctions, and more elaborate "spin electronic" devices, and offers the opportunity to study frustration[3] and the interactions of ferromagnetic and antiferromagnetic orders in low dimensions. The effect originates from the interfacial coupling of atomic spins across a ferromagnetic (F) and antiferromagnetic (AF) interface, the principal manifestation of which is a unidirectional anisotropy in the F layer.[4–6] The main characteristic features which arise from the phenomenon are the offset of the F hysteresis loop from zero, referred to as the exchange bias field (H_e), and its associated coercivity enhancement (H_c).

However, the precise microscopic mechanism which controls the interfacial coupling is still a somewhat contentious topic. Large amounts of both experimental and theoretical works[7] have highlighted the complex interplay of parameters that influence the effect. It is now evident that the simple model that was first proposed by Meiklejohn and Bean—which assumes an ideally smooth, magnetically uncompensated surface containing a rigid spin structure—is inadequate in explaining the biasing. Foremost, such perfect interfaces do not exist in reality, but, moreover, this model is also unable to explain all the rich features associated with the effect; for instance, coercivity enhancement[8–10] and training effects[11,12] are common to all systems to varying degrees. It is also unable to address the asymmetrical reversal of the magnetization in such systems,[13] the AF layer thickness dependence,[12,14,15] and the lower than expected experimentally obtained values for the exchange bias field. In spite of this, it does highlight that an offset in the hysteresis loop will only be permitted when the anisotropy of the antiferromagnet K_{AF} is adequately larger than the interlayer exchange coupling $J_{AF\text{-}F}$. The importance of the AF anisotropy was also demonstrated in an artificial exchange bias $[Co/Ru]_{10}/[CoPt/Ru]_{10}$ system, where the shift in the hysteresis loop was only shown to be present under these conditions.[16] It has also been demonstrated that the enhancement in the coercivity at both the onset and disappearance of biasing is due to these terms being similar in magnitude, giving rise to a reversible magnetic component in the AF.[17]

Several theoretical models have evolved based on the formation of domains in the antiferromagnet to reduce the coupling strength.[4,5,18–22] The most encouraging models have been those which involve random variations in the local biasing due to defects[22,23] or roughness,[21] the essence of which is to dilute the spins involved, reducing the anisotropy and the exchange interaction. However, at present, the interface structure is generally assumed (with very few exceptions[24]) to be that of the bulk antiferromagnet, the main reason being the extreme difficulty in experimentally ascertaining the precise structural and magnetic nature of the buried interface at the necessary atomic scale. Even for the most ideal samples, it is hard to imagine that there will no reordering of the magnetic, crystallographic, and chemical structure at the interface region. This will give rise to magnetic disorder and/or spin dilution. It has been demonstrated, in an epitaxial Co/FeMn sample, how paramount the local atomic spin structure is for exchange bias.[25] It was shown that the atomically flat planes did not play a role, whereas the monolayer steps (atomic scale roughness) that are present at the interface mediates the magnetic coupling across the interface. This may also resolve the quandary of why a nominally fully compensated AF surface is able to pin a ferromagnetic layer.[26]

However, the bulk AF spin structure also plays an important role. Recent experiments have shown that it is possible to manipulate the bias field by ion irradiation of the samples.[27–31] The experiments have demonstrated that it is possible to modify the exchange bias properties by manipulating the level of disorder depending on the ion dose and energy, in line with recent theoretical models.[4] In the majority of these experiments, the complete system has undergone the irradiation process, including the ferromagnet. Interestingly, in all cases, the experiments have been undertaken in the presence of an external magnetic field. This implies that the system is undergoing a local thermal treatment, where the biasing is being reset locally, hence the necessity for an applied field. In a similar vain, nonmagnetic additives have been introduced into the AF layer during the deposition[32–35] which have also shown that it is possible to manipulate the exchange bias in line with the domain state model.

From current theoretical models and accompanying experimental work, it is established that there are domains in the AF layer. However, there are still questions regarding the formation and type. Do the domains nucleate at the interface due to disorder, as in the domain model of Malozemoff,[21] or are they more in line with the domain state model of Nowak *et al.*?[36]

Another class of experiments is those where spacers are introduced between the F and AF layers. The exchange bias field is essentially dependent on the relative strengths of K_{AF} and $J_{AF\text{-}F}$, and this has been investigated by a number of groups, where spacer layers have been introduced between the AF and F layers to manipulate the strength of the coupling.[37–43] These studies seem to indicate that exchange bias is not necessarily a consequence of a direct exchange (nearest-neighbor) coupling mechanism. There have been contradictory reports that the exchange bias across the spacer layer is long range in nature and decays exponentially,[37] while others have reported it to be either oscillatory[43] or very short range in nature,[38] with any long-range effects ascribed to the presence of pinhole defects in the spacer.

In order to provide further insight into these questions, we report in this paper on the effects of inserting a δ dusting of various elements to induce disorder at both the interface and in the bulk of the AF layer in a controlled manner. This was done by depositing a submonolayer of both magnetic and nonmagnetic impurities in order to induce changes in the magnetic disorder on the atomic level.

II. EXPERIMENTAL METHODS

The Co/IrMn system was studied experimentally within a simple spin-valve structure. A series of exchange biased spin-valve films was deposited by dc magnetron sputtering at an argon working pressure of 2.5 mTorr. The base pressure prior to the deposition was of the order of 2×10^{-8} Torr. The substrates used were Si(100) with the native oxide layer intact, cleansed in acetone and isopropanol. The samples were deposited at ambient temperature and through masks to ensure a constant film area from sample to sample. The system allowed 15 samples to be deposited during the same vacuum cycle, which permitted 15 spin-valve structures Ta (75 Å)/Co(40 Å)/Cu(23 Å)/Co(26 Å)/IrMn(x Å)/δ layer/IrMn($120-x$ Å)/Ta(50 Å) to each specimen set, grown in indistinguishable conditions which eliminate, as far possible, sample-to-sample variations within a run: these variations are very small as can be seen in certain data sets later in the paper. However, there can be more noticeable variations in these properties from one sputtering run to the next. Hence, an important part of our experimental methodology is to prepare an undoped control sample in each run, to which the properties of the doped samples can be compared. In the data presented below for the H_e and H_c dependences on impurity layer thickness and position in Figs. 2–5, the 14 data points are the doped samples from a single sputtering run, while the dotted line indicates the values for these fields displayed by the control sample.

The IrMn was deposited from a Mn target with chips of Ir attached to its surface, and energy dispersive x-ray absorption spectroscopy yielded a composition in the deposited film of $\sim Ir_{25}Mn_{75}$. Deposition rates were determined by measuring the thickness of test films by low angle x-ray reflectometry, and were typically in the range of 2–3 Å/s. X-ray diffraction showed that such samples are predominantly fcc with a (111) texture. We did not detect any changes in texture in a representative selection of doped samples measured by this technique, presumably since the δ layers are so thin. No postannealing steps were required, since the pinning direction was set by a 200 Oe in-plane forming field applied to the sample during the deposition of all the layers in this top spin-valve configuration.

The distance x from the AF/F interface to the impurity layer was zero in some cases, but could also be an experimental variable. An IrMn layer thickness of 120 Å was chosen for two reasons: the first being that it is sufficiently thick that any fluctuations in the IrMn thickness would have a negligible effect on the exchange biasing, and the second is that it allowed the possibility of placing the impurity layer sufficiently away from the interface, but still within the bulk of the layer to investigate disorder effects. Previous work has established an in-depth understanding of both the temperature and thickness dependence of the exchange bias for this Co/IrMn system.[12] It has been shown that the critical thickness at which biasing is fully established is approximately 40 Å at room temperature. For greater thicknesses, the biasing effect is found to be constant in an undoped layer. It should be noted that the δ-layer method has been also employed to investigate electronic structure effects on giant magnetoresistance in spin valves[44] and interlayer coupling in multilayers.[45] (The δ-layer method and the effects on giant magnetoresistance in spin valves[44] and interlayer coupling in multilayers[45] have been previously described.)

In comparison to the ion irradiation studies where the complete structure undergoes irradiation, the δ dusting only generates disorder on the atomic length scale. This also allows information on the position dependence of the δ dusting on exchange bias. Studies up to now have solely considered nonmagnetic defects to produce disorder. A foreign magnetic impurity will also cause both structural and magnetic disorders through frustration, for example, besides being polarized. One should be aware that even though the particle size of the magnetic impurities will be in the paramagnetic regime, the particle will have a Curie point dictated by its surrounding magnetic environment through proximity exchange effects. Hence, for particles within the IrMn layer, the Curie point would be that of the Néel point of the IrMn, in this case, 250 °C.

The spin-valve structure allowed the free Co layer within the spin valve to be used as a control layer, to which the properties of the exchange coupled Co layer could be directly compared. The effect of the free layer on the pinned layer properties was minimal: orange-peel coupling fields were never more than a few oersted. It also allowed magnetotransport measurements to be performed; the resistance measurements were done using a standard four point probe dc technique. Typical (300 K) magnetoresistances of our spin valves were ~7%, while typical (300 K) sheet resistances were 10 Ω/square. Magnetic characterization was done using a vibrating sample magnetometer (VSM) and a

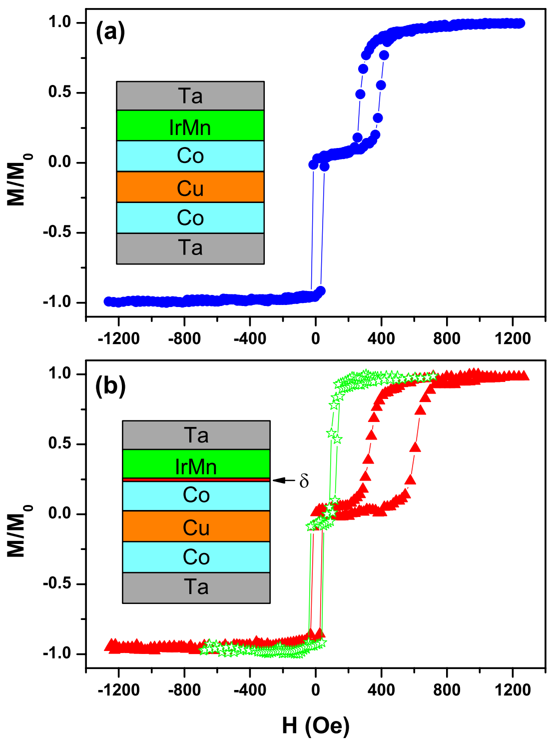

FIG. 1. (Color online) Spin-valve hysteresis loops measured by VSM: (a) undoped control sample with Co(26 Å)/IrMn(120 Å) exchange biased bilayer, and (b) doped samples with Co(26 Å)/Fe(1.0 Å)/IrMn(120 Å) (red triangles) and Co(26 Å)/Ta(1.0 Å)/IrMn(120 Å) (green stars) pinned layers. The increase or decrease in bias bias field upon δ doping is accompanied by a commensurate change in the coercivity.

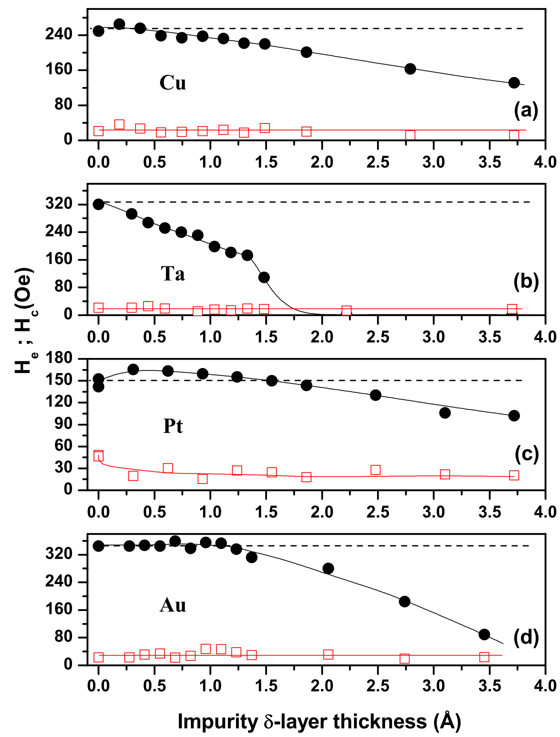

FIG. 2. (Color online) The dependence of H_e (solid circles) and H_c (open squares) on the thickness of a δ dusting of nonmagnetic impurities inserted at the Co/IrMn interface. The solid lines are a guide for the eye. The dashed lines show the values obtained for undoped control samples grown in the same sputtering runs.

magneto-optical Kerr effect apparatus. All the data we shall show for H_e and H_c were acquired at room temperature.

III. RESULTS AND DISCUSSION

We begin by showing in Fig. 1 some hysteresis loops that illustrate the clear spin-valve switching in our samples as well as the marked effects even small amounts of δ impurity can have on the exchange bias in this system. In Fig. 1(a), we show the typical result obtained for an undoped "control" sample. The pinned and the free layer loops are easily identifiable, from which the exchange bias field and coercivity values are straightforwardly obtained by the usual means: H_e is the offset of the pinned loop center from zero field; H_c is half its width. The effects on exchange bias of a 1 Å Fe or Ta δ layer at the AF/F interface are shown in Fig. 1(b). The most striking effect is the large increase of the exchange bias field for the introduction of the Fe, accompanied by an enhancement in H_c. One finds that exchange bias field approximately doubles depending on the Fe dusting thickness [Fig. 3(a)] employed. Using $J_{\text{AF-F}}=H_e M_s t_F$, where $J_{\text{AF-F}}$ is the interfacial exchange energy per unit area, and M_s and t_F are the magnetization and thickness of the ferromagnetic layer, respectively, values of 0.17 and 0.35 mJ m^{-2} are obtained for the interfacial exchange energy for the control and Fe-doped case, consistent with much stronger exchange bonds across the interfacial sites. Meanwhile, the introduction of Ta reduces the interfacial exchange energy to 0.07 mJ m^{-2}, consistent with Ta breaking interfacial exchange bonds between Co and IrMn sites. H_c is reduced by the introduction of Ta.

In the rest of this paper, we describe in detail the effects of a selection of impurities, placed at the Co/IrMn interface and moved away from it into the IrMn layer, on H_e and H_c.

A. Interfacial δ layers

The effect of placing the nonmagnetic impurities Cu, Ta, Pt, and Au at the Co/IrMn interface ($x=0$) on H_e and H_c is presented in Fig. 2 as a function of the dusting layer thickness. The solid lines are a guide for the eye, and the horizontal dashed lines indicate the value of H_e for the control samples without any δ dusting. In general, the exchange bias field decreases as the dusting becomes thicker. (Here, the thickness is defined as the average equivalent thickness for the quantity of material deposited.) It is clear that materials that make good spacer layers for indirect exchange coupling via the Ruderman-Kittel-Kasuya-Yosida (RKKY) mechanism, such as Cu and Au, tend to suppress H_e less rapidly compared to materials such as Ta. For the Ta impurity, there is a monotonic decrease for thicknesses up to 1.5 Å, before H_e rapidly collapses to zero at that point. Interestingly, this length scale is significantly smaller than the equivalent thickness of a monolayer (3.3 Å bcc), and therefore, is unlikely to be a consequence of the formation of a continuous Ta layer.

Extrapolating the curves for Cu, Pt, and Au, one finds that H_e diminishes to zero at impurity thicknesses of approximately 6, 8, and 4 Å, respectively. These thicknesses are greater than that required to form a monolayer. It could be conceived that this is the point at which the dusting coalesces to form a continuous layer. This is feasible, since metallic superlattice structures have shown that it is, indeed, possible to obtain continuous spacer layers of the order of 2 monolayers.[46] The small length scales involved (<10 Å) clearly suggest that exchange interaction across the interface is very short range in nature, and so the biasing appears to be due solely to direct exchange interactions between spins in the F and AF layers. This is in sharp contrast to the findings of previous work,[37] where the exchange field was reported to exponentially decay over a length scale of ~50 Å. However, our low dusting levels are in agreement with the work of Thomas *et al.*[38,40] In order to ensure that there were no long-range coupling effects, films were grown where 10 Å of Ta/Cu dusting was used. No biasing was observed from these films. Keeping this in mind, it is even more puzzling why a dusting of 1.5 Å of Ta would suppress the biasing. This must be less than a monolayer, leaving large areas of direct exchange between the Co and IrMn layers. A possible explanation is that a Ta atom must screen exchange bonds involving neighboring atomic sites as well as its own by creating an extended defect in the electronic structure. It should be noted in systems where Ta is placed, for example, next to Permalloy ($Ni_{81}Fe_{19}$) that a chemical reaction takes place between the two layers, giving rise to a dead layer. This has an effect of reducing the moment[47–49] of the layer by influencing the local electronic structure. Also, it has been shown that 2 Å of Ta is not only discontinuous but has significant influence on the grain size and crystal structure[42] of IrMn, in comparison to Cu or Pt. In this situation, magnetic disorder and structural changes are present, which can explain the stark reduction in H_e. Even a small change in the lattice constant of the IrMn layer will drastically alter the K_{AF} and, consequently, its magnetic properties. This can be seen by examining H_c as a function of Ta thickness, where the authors have found a slight peak in H_c, which generally indicates some reversible magnetic process in the AF spin structure.

The Pt dusting, however, also exhibits an additional feature where H_e increases by ~10% above that for the control sample for a δ dusting <1.5 Å before then gradually decreasing toward zero. This effect is remarkably similar to what has been observed in perpendicular exchange bias systems, where the addition of a Pt spacer layer is said to induce a better collinear alignment of the Co spins out of the plane.[40] This gives rise to an increase in H_e. In the present case, the spins for both layers are confined to the easy plane of the film by the shape anisotropy. One possibility is that the Pt is substituting for the Ir to form a chemically ordered $L1_0$ phase of PtMn on a localized basis, which itself is an AF material. PtMn possesses a larger anisotropy and is, therefore, able to orientate a larger number of Co spins to be collinear with the unidirectional anisotropy at the interface. This will have the effect of increasing H_e. Further increments of Pt (>0.4 Å) simply reduces H_e as with the other impurities, presumably by weakening interfacial exchange bonds.

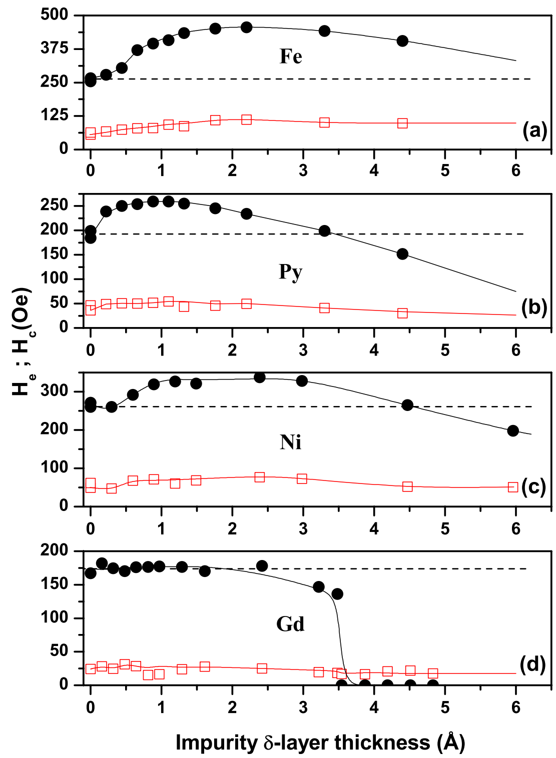

FIG. 3. (Color online) The dependence of H_e (solid circles) and H_c (open squares) on the thickness of a δ dusting of magnetic impurities inserted at the Co/IrMn interface. Solid lines are a guide for the eye. The dashed lines show the values obtained for undoped control samples grown in the same sputtering runs. The symbol Py refers to $Ni_{80}Fe_{20}$, the Permalloy composition.

Before moving on, we note that, in all cases, H_c remains approximately constant for all dusting levels, indicating that there is no substantial change in the AF reversible spins in the bulk or interface, which is generally associated with any enhancement or reduction of H_c.[17] The lack of any enhancement even at the point where the biasing vanishes [Fig. 2(b)] is generally interpretated to be the point at which the biasing becomes reversible before vanishing as a function of AF layer thickness or temperature.[50] This would imply that the impurity is simply diluting or screening the exchange interaction of the spins which are associated with the biasing across the F/AF interface.

The effects on H_e and H_c of placing various magnetic impurities at the Co/IrMn interface is shown in Fig. 3. Since $H_e \sim 1/Mt$, we would expect that increasing the total ferromagnetic (FM) layer thickness by adding this material would give a dependence where $H_e \sim (M_{Co}t_{Co} + M_{impurity}t_{impurity})^{-1}$, hence decreasing the bias field. Nevertheless, the most striking feature is the large increase in H_e in the appropriate δ-layer thickness range for the 3*d* metals Fe and Ni, and Permalloy (Py=$Ni_{80}Fe_{20}$). For all these three, a broad peak in H_e approximately at 1–2 Å of impurity is observed. The insertion of the Fe dusting increases H_e by some 72%, whereas for NiFe, it is 34%, and for the Ni dusting, the rise is 29%. As might be expected, the general form of the data for the NiFe alloy falls between those for the pure elemental Fe and Ni impurity layers. It is interesting to note that the magnetization of the pinned layer material, Co, falls between that of Fe and Ni. This means that Fe impurities will be increasing the surface magnetization of the pinned layer, while Ni impurities will reduce it. However, both are capable of increasing the bias field above that for a control sample. This suggests that the increase in bias is somehow related to an inhomogeneous magnetic interface. An interesting remark is that the percentage increase is roughly proportional to the saturation magnetization of the dusting element in bulk form, although we do not have a simple explanation for this.

We have also used a 4*f* ferromagnet impurity, Gd, the moment of which is known to couple antiferromagnetically to that in 3*d* materials. The results for Gd are shown in the bottom panel of Fig. 3. Here, the effect is quite different, with almost no change in the bias field until a critical thickness of about 3.5 Å, when H_e drops abruptly to zero. This thickness corresponds roughly to a monolayer. Although the Gd was barely above its bulk Curie temperature of 293 K, we should expect that it has some ferromagnetic order as the moments will be in a strong exchange field from the Co with which it is in intimate contact. Hence, it seems that the Gd moments do not couple to those in the IrMn which are responsible for biasing, although why this should be so is not clear to us at present. It should be noted that there was no evidence of any biasing at lower temperatures of a single Gd layer.

B. δ layers in the bulk

The effects of inserting a nonmagnetic δ layer of 1 Å thickness into the AF layer a distance x from the interface are shown in Fig. 4 for the same four impurity materials as in Fig. 2. In no case is there any increase in H_e over the control samples. However, as the δ dusting is moved into the IrMn for the first few angstrom away from the interface, H_e decreases, accompanied by a slight increase in H_c. As the δ layer is moved further still from the interface, H_e recovers to the value shown by the control samples once x exceeds ~20 Å. The length scale of 20 Å seems to be independent of the dusting material used. The magnitude of the dip in bias field seems again to be correlated to the indirect exchange coupling strength of the material as a spacer layer for RKKY coupling (Fig. 2). Pt has the least effect, followed by Au, Cu, and then Ta, which also has a detrimental effect at the interface as shown in Fig. 2.

This implies that the H_e enhancement originates from a purely interfacial magnetic effect and, therefore, cannot be a result of changes in the domains in the bulk of the antiferromagnet of the type that is assumed in dilution[51] or ion irradiation experiments.[27–31]

We also used a slightly greater dusting of 1.5 Å of Ta, which at the interface completely suppresses the biasing, but as the dusting is moved away from the interface, H_e reappears at approximately $x\sim20$ Å and fully recovers to that of the control samples by $x\sim30$ Å. We also found that there is peak in H_c at the onset of H_e as usual. This contradicts an investigation where a Au layer was moved away from the NiO/Co interface,[41] where it was found that the biasing totally disappeared as the Au layer was moved away from the

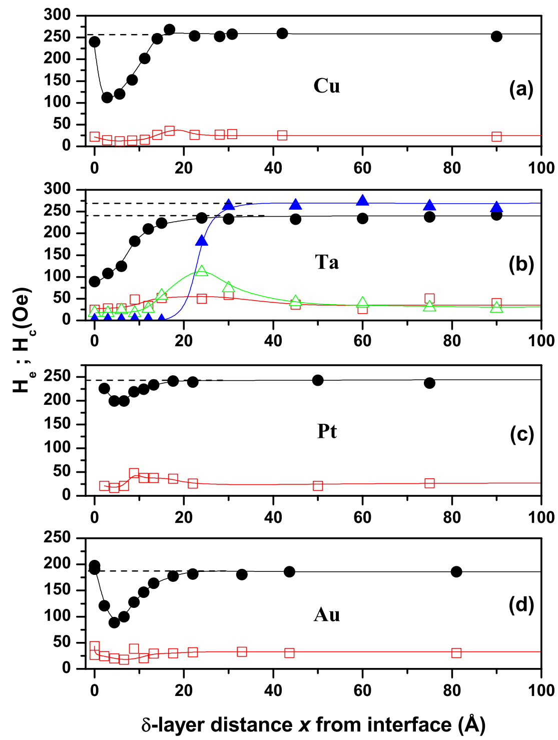

FIG. 4. (Color online) The dependence of H_e (solid circles) and H_c (open squares) on the position x of a 1 Å δ layer from the Co/IrMn interface. Solid triangles (H_e) and open triangles (H_c) in (b) represent a δ dusting of Ta of 1.5 Å. The dashed lines show the values for H_e obtained for undoped control samples grown in the same sputtering runs.

interface. The difference might arise from the differences in magnetic energy in the NiO/Co samples compared to the IrMn/Co ones. The effects of the thicker Ta layer bear a striking resemblance to the AF layer thickness studies that have been previously carried out on this materials system.[17] Similar characteristic length scales are present for the onset and saturation of H_e along with a peak in H_c at the onset of biasing. This suggests that the Ta layer is thick enough here to divide the IrMn into two magnetically disconnected parts. Only the part that is adjacent to the FM layer contributes to the exchange bias; the other part plays no role. For low values of x, the thickness of the part of the IrMn layer which is in contact with the Co is so low that this layer has a granular nature. Hence, it is unable to provide bias for the same reasons as in studies where the total AF layer thickness is varied.

The effects of moving a magnetic δ layer of 1 Å thickness into the IrMn layer are shown in Fig. 5: the three elemental impurities used in the experiment reported in Fig. 3 appear here along with Co. The elements Gd and Co were seen to have no significant effect on either H_e or H_c for any value of x. On the other hand, there is a clear dependence of these two quantities on x for the Ni and Fe layers to be seen in the data. The trend is similar to that of the nonmagnetic δ layers for small values of x, where there is a dip in H_e at approximately $x=5$ Å. However, as the layer is moved further from the interface, not only does the biasing recover and saturate by

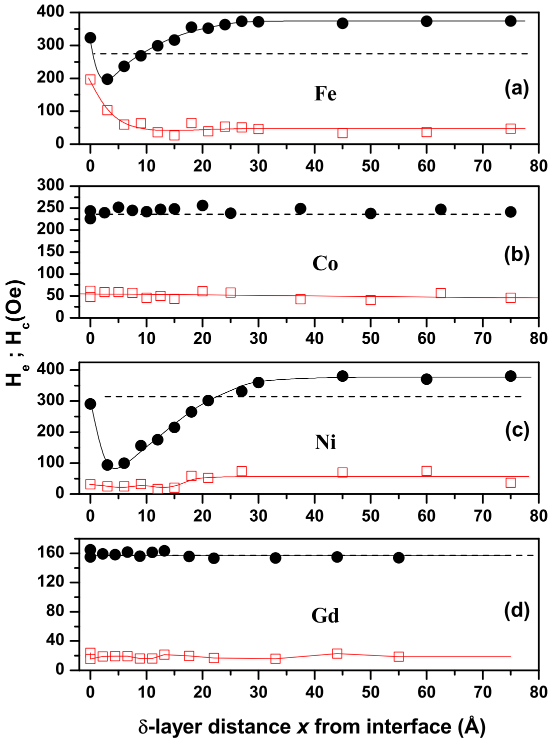

FIG. 5. (Color online) The dependence of H_e (solid circles) and H_c (open squares) on the position x of a magnetic δ layer of 1 Å thickness from the Co/IrMn interface. The dashed lines show the values obtained for undoped control samples grown in the same sputtering runs.

30 Å, the magnitude also increases in comparison to the control samples by 20% for Ni and 34% for Fe. In general, no obvious trend with the position of the δ layer is evident in H_c. There is enhancement in H_c when the Fe is present at the interface, but this falls rapidly back to the control sample level once beyond 5 Å. This is also evident in Fig. 3, where a slight increase in H_c is observed.

As with the nonmagnetic elements, the dip in H_e is attributed to the dilution of the interfacial magnetic moment and anisotropy for the Fe and Ni elements: given that these are magnetic elements, we should not expect a significant depression in the local exchange interaction strength. One can speculate that the δ layer is neutralizing the uncompensated moments associated with the biasing. It may be significant that while FeMn,[52] CoMn,[53] NiMn,[54] and $GdMn_2$ (Ref. 55) all have antiferromagnetic phases, only FeMn and NiMn show a significant exchange bias at room temperature.[56] Exchange bias from antiferromagnetic CoMn is generally either nonexistent or weak.[57] We are unaware of any reports of attempts to observe an exchange bias using a GdMn-based AF layers. At the interface, the Fe and Ni simply couple ferromagnetically with the Co layer, whereas immediately within the IrMn layer, they couple antiferromagnetically with the uncompensated spins in the vicinity of the interface, in this manner effectively reducing the net interfacial magnetization. Elements such as Au or Cu reduce the biasing because they possibly form the classical spin glass phases of CuMn (Ref. 3) and AuMn. At room temperature, the spin glass would behave as a paramagnetic entity and similarly reduce the net interfacial magnetization. For these reasons, one might obtain a dip in H_e as a function of position. Away from the interface, the Ni and Fe create an additional AF system (FeMn/NiMn) within the IrMn, which enhances the biasing. What is intriguing is the lack of any effect of the Co or Gd on the δ-layer position. One can only infer that the Co and Gd atoms are easily accommodated into the magnetic structure of the IrMn layer for the dusting levels employed and, therefore, have a negligible effect on the local anisotropy.

The results of Fe and Ni seem to suggest that not only is the interfacial anisotropy paramount for exchange biasing (the dip), but the final magnetic state is also influenced by the bulk magnetic state of the AF layer due to the enhancement in H_e beyond 30 Å. These results seem to be in agreement with the diluted domain state models and the ion irradiation experiments.

IV. CONCLUSION

We have shown that magnetic disorder is a key ingredient in understanding the exchange bias phenomenon by studying the effects of inserting impurity δ layers of various elements at both the Co/IrMn interface and at given points within the IrMn layer itself. The experiments have shown the importance of disorder in the vicinity of the interface and throughout the bulk of the AF layer, and is consistent with the domain state model. By using both magnetic and nonmagnetic δ layers, it is possible to conclude that it is the magnetic disorder which seems to dominate and control the exchange bias effect. Any effect which is able to generate magnetic disorder will, therefore, influence the exchange bias. In general, nonmagnetic elements were found to reduce the exchange coupling, the exception being Pt, where larger anisotropies are induced. On the other hand, when placed correctly, the magnetic elements induce a stronger exchange bias due to the increase in magnetic disorder by inducing stronger exchange bonds or anisotropy at the doped atomic sites. Overall, we have observed a rich variety of behavior that we hope will provide a spur to the development of theories that treat disorder in exchange bias systems. Also, these results demonstrate a means of tailoring and improving the magnitude of exchange anisotropy in device applications.

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