Influence of ferromagnetic-antiferromagnetic coupling on the antiferromagnetic ordering temperature in Ni/Fe_xMn_{1-x} bilayers

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(Received 2 December 2009; revised manuscript received 11 February 2010; published 26 March 2010)

We present a detailed study on epitaxial bilayers made up of ferromagnetic (FM) Ni and antiferromagnetic (AFM) Fe_xMn_{1-x} layers on Cu(001). The AFM ordering temperature (T_{AFM}) and the coupling at the interface of FM and AFM layer are deduced from polar magneto-optical Kerr effect measurements at different temperatures. The enhancement of coercivity for samples with different Fe_xMn_{1-x} layer thickness, Fe concentration, and FM-AFM interface roughness reveals that T_{AFM} only depends on the layer thickness. The FM-AFM coupling strength is determined by the Fe concentration of the Fe_xMn_{1-x} layer and the interface roughness, but as the first two measurement series clearly show, these do not affect the ordering temperature, unlike earlier results for in-plane magnetization. We explain this difference by assuming that the spin structure of the AFM is distorted from the 3Q structure of the bulk material, in a way that depends on the magnetization direction of the adjacent FM layer. Additionally we discuss the dependence of FM-AFM coupling strength and AFM magnetic anisotropy on Fe concentration and interface roughness concluded from the thickness dependence of exchange-biased hysteresis loops.

DOI: 10.1103/PhysRevB.81.104420 PACS number(s): 75.70.Ak, 75.40.Cx, 75.50.Ee, 75.70.Cn

I. INTRODUCTION

Many data storage and spintronic devices take advantage of the magnetic interaction between antiferromagnetic (AFM) and ferromagnetic (FM) layers.[1] The basic understanding of the effects involved at the interface of these bilayers is important for the further development of such devices. For example, the knowledge of the mechanisms determining the magnetic ordering temperature of the AFM material is very valuable considering the recent interest in heat-assisted magnetic recording[2] and the concurrent concern in temperature-dependent effects.

We have previously shown that proximity effects at the interface of FM and AFM layers lead to a strong dependence of the ordering temperature (T_{AFM}) of an AFM Fe_xMn_{1-x} film on the magnetization direction of an adjacent FM overlayer.[3] There are two possible mechanisms that can explain this effect: Either the FM-AFM coupling strength is different for in-plane and out-of-plane magnetization, thus leading to the observed influence on T_{AFM}, or a different distortion of the three-dimensional noncollinear AFM spin structure is responsible for the different AFM ordering temperatures. To decide which of these two mechanisms is the predominant one and to get a deeper understanding about if and how the spin structure influences the proximity effect and therewith ordering temperature and magnetic coupling in FM-AFM bilayers, we performed a systematic study of out-of-plane magnetized epitaxial Ni/Fe_xMn_{1-x} bilayers. Samples consisting of 15 monolayers (MLs) ferromagnetic Ni above and below antiferromagnetic Fe_xMn_{1-x} layers of different thickness were deposited on a Cu(001) single-crystal substrate. We investigate the influence of the Fe_xMn_{1-x} layer thickness, Fe concentration, and AFM-FM interface roughness on coercivity, magnetic reversal, and AFM ordering temperature in these single-crystalline epitaxial AFM-FM bilayers. We find that interlayer roughness and Fe concentration have an effect on the AFM-FM coupling strength but not on T_{AFM}. The dependence of the coupling strength is also reflected by the exchange-bias field. We therefore conclude that it is the spin structure inside the Fe_xMn_{1-x} layer that determines the ordering temperature and not the interface coupling strength.

The spin structure in bulk Fe_xMn_{1-x} is of the 3Q type[4,5] but could well be distorted at the interface or in thin films due to the interaction with an adjacent FM layer. Wu *et al.*[6] have shown that Fe_xMn_{1-x} induces an anisotropy to the Ni layers favoring an in-plane alignment of the Ni spins. Previous research on the antiferromagnetic order in ultrathin Fe_xMn_{1-x} films has shown that the spin structure in contact to both in-plane and out-of-plane magnetized FM layers remains three dimensional and noncollinear but must not necessarily be of the bulk 3Q type.[7] Our results show that indeed a reorganization of the spin structure depending on the magnetization direction of the adjacent layer is likely to occur in Fe_xMn_{1-x}.

II. EXPERIMENTAL DETAILS

All samples were prepared under ultrahigh vacuum (UHV) conditions at a base pressure of $\approx 5\times 10^{-10}$ mbar. The single-crystalline Cu(001) substrate was cleaned by repeated cycles of Ar-ion sputtering at 1–2 keV and subsequent annealing at 900 K. All FM and AFM films were deposited by (co-)evaporation from high-purity metal rods at room temperature (RT) with a typical rate of ≈ 1 ML/min. The thickness of the films was determined by *in situ* medium energy electron diffraction and the Fe concentration in Fe_xMn_{1-x} was identified by Auger electron spectroscopy.[8]

Three slightly different sample series were prepared: series (A) are 15 ML Ni/Fe_xMn_{1-x}/Cu(001) bilayers with different Fe_xMn_{1-x} layer thickness and Fe concentration x. For series (B) the layer sequence was reversed, i.e., Fe_xMn_{1-x}/Ni/Cu(001). For some of these samples the Ni layer was annealed to 450 K for 20 min and then cooled down to room temperature before deposition of the Fe_xMn_{1-x}

TABLE I. Overview of the three sample series and measurements.

Series	Layer sequence	Determination of	Discussed in Sec.
(A)	$Ni/Fe_xMn_{1-x}/Cu(001)$ as prepared	$H_C \rightarrow T_{AFM}$ vs concentration and thickness	III A–III C
(B)	$Ni/Fe_xMn_{1-x}/Cu(001)$ as prepared, $Fe_xMn_{1-x}/Ni/Cu(001)$ annealed/not annealed	$H_C \rightarrow T_{AFM}$ vs roughness and layer sequence	III B and III C
(C)	Stepwise grown $Fe_xMn_{1-x}/Ni/Cu(001)$	H_C, H_{EB} vs thickness and concentration at RT	III D

layer. The samples of series (A) were used to study the effects of Fe_xMn_{1-x} layer thickness and Fe concentration, the samples of series (B) reveal the dependence of FM-AFM interface roughness on the AFM ordering temperature and magnetic coupling.

In the $Fe_xMn_{1-x}/Ni/Cu(001)$ series (C) samples the Fe_xMn_{1-x} layer was step-by-step prepared and measured at room temperature to yield an Fe_xMn_{1-x} thickness dependence of the coercivity and exchange-bias field. In all the sample series the ferromagnetic Ni layer always had a thickness of 15 ML to achieve out-of-plane easy-axis magnetization[9] and a Curie temperature of ≈530 K (to be well larger than the AFM ordering temperature). The Fe concentration was varied from 40% to 60% to make sure that the Fe_xMn_{1-x} layer was growing epitaxially on Cu(001) and behaving as an antiferromagnet.[10]

Hysteresis curves of the bilayers were taken by polar magneto-optical Kerr effect (MOKE) measurements under UHV conditions in an external field of up to 200 mT. Varying temperatures from 140 to 400 K could be achieved by liquid-nitrogen cooling and simultaneous resistive heating. The minimum temperature limit is determined by the maximum achievable magnetic field for the hysteresis loops. Temperature stabilization within ±2 K was sustained by a temperature controller using thermocouples. Table I gives a short overview of all three sample series and the measurements performed.

III. RESULTS AND DISCUSSION

First of all, in Sec. III A we discuss the temperature dependence of the AFM ordering temperature as function of (i) Fe_xMn_{1-x} layer thickness and (ii) Fe concentration. The thickness of the Fe_xMn_{1-x} films was varied between 6 and 9 ML as in this regime the ordering temperature T_{AFM} could be determined without heating the sample to more than 400 K. After heating to this temperature no irreversible change in the magnetic properties was observed.

In Sec. III B we analyze the influence of the AFM-FM interface roughness on the ordering temperature, by studying the samples from series (A) and series (B). Section III C describes the role of the magnetic coupling between the AFM and the FM layer.

Finally, in Sec. III D we investigate the coercivity and exchange-bias field as a function of the AFM layer thickness. These measurements were only performed at room temperature.

A. AFM ordering temperature—dependence on thickness and Fe concentration

Figure 1 shows the temperature-dependent coercivities of three samples of series (A) with the same Fe_xMn_{1-x} layer thickness but different Fe concentration. The coercivities were obtained from MOKE hysteresis curves at different temperatures (examples can be seen in the inset of Fig. 1). For temperatures $\geq T_{AFM}$, the Fe_xMn_{1-x} layer is paramagnetic so that the coercivity is that of the FM layer itself and only shows a weak linear dependence on the temperature. For temperatures $\leq T_{AFM}$, the Fe_xMn_{1-x} layer becomes antiferromagnetic and couples to the FM layer, which results in an increase in the coercivity. The point of deviation from the linear behavior is indicated by an arrow in Fig. 1 and marks the ordering temperature T_{AFM} of the antiferromagnet Fe_xMn_{1-x}. For all three curves this temperature is the same although the slopes in $H_C(T)$ are different. More details about these slopes will be discussed in Sec. III C.

Note that we slightly changed the method to determine the ordering temperature in contrast to previous work[3,8] where the method of intercepting tangents to deduce T_{AFM} was used. The difference is that the temperature range used here is much broader and does not only show the two linear parts of $H_C(T)$. At low temperatures the $H_C(T)$ behavior becomes nonlinear and hence the intercept method is not appropriate anymore. This is why we used only one linear fit for the high-temperature regime and determine T_{AFM} as the

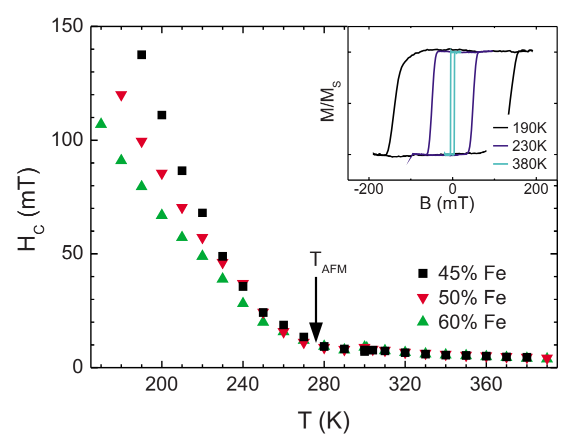

FIG. 1. (Color online) Temperature-dependent coercivities obtained from hysteresis curves of 15 ML Ni on 6.5 ML Fe_xMn_{1-x} for different Fe concentration [series (A)]. The inset shows examples of normalized polar MOKE hysteresis curves of the $Fe_{45}Mn_{55}$ sample at different temperatures.

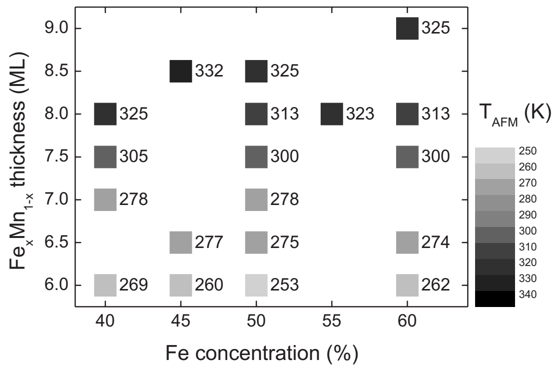

FIG. 2. Grayscale-coded AFM ordering temperature (T_{AFM}) of all samples from series (A) in dependence of the Fe_xMn_{1-x} thickness and Fe concentration. Numbers denote T_{AFM} in Kelvin (± 5 K).

point where H_C deviates by more than 3 mT from the linear fit to the high-temperature regime, as the typical scatter of individual data points is 1–2 mT.

A compilation of the ordering temperatures is presented in Fig. 2 for all samples of series (A). One can see the roughly linear dependence of T_{AFM} for increasing Fe_xMn_{1-x} layer thickness. Earlier studies[3,8] of in-plane and out-of-plane magnetized bilayers showed the same increase in T_{AFM} for increasing Fe_xMn_{1-x} layer thickness. This result can be explained by finite-size effects in which thinner layers lead to a smaller total exchange coupling and thus to a lower ordering temperature.

The same earlier studies showed an increase in T_{AFM} with decreasing Fe concentration. However, these measurements were performed on in-plane magnetized $Co/Fe_xMn_{1-x}/Cu(001)$ (Ref. 8) and $Co/Ni/Fe_xMn_{1-x}/Cu(001)$ (Ref. 3) samples. The same behavior seemed to show up also for out-of-plane measurements in $Ni/Fe_xMn_{1-x}/Cu(001)$ bilayers[3] but this was concluded only from one data point and can not be confirmed by the systematic investigation of this work. In summary we conclude from the measurements of sample series (A) that T_{AFM} decreases for decreasing Fe_xMn_{1-x} layer thickness but is independent of the Fe concentration.

B. AFM ordering temperature—dependence on interface roughness

The out-of-plane measurements[3] additionally seemed to show a dependence of T_{AFM} on the filling of the Fe_xMn_{1-x} layer: a half-integer-filled layer showed a lower ordering temperature than the integer filled layers. The coupling between FM and AFM layers is explained by the interaction of uncompensated spins at the interface.[11,12] The bulk spin configuration of Fe_xMn_{1-x} with an Fe concentration around 50% is the 3Q structure,[4,13] in which the spins at the corners of a tetrahedron point toward its center. In this spin configuration the spin component parallel to the interface is compensated in {100} planes but there is a resulting uncompensated moment perpendicular to the interface pointing out of and into the plane alternately in subsequent {100} planes.[3] This leads to the assumption that the coupling might be stronger for a

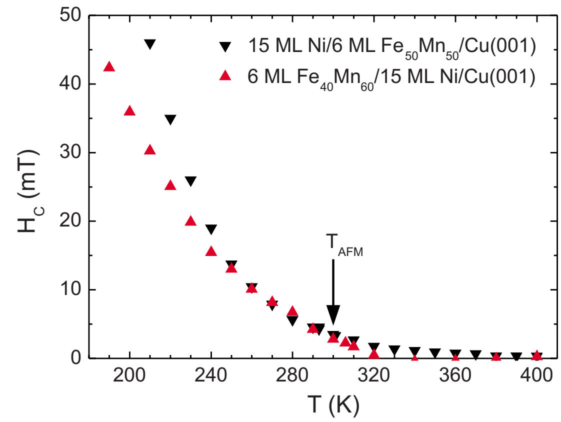

FIG. 3. (Color online) Temperature-dependent coercivities of two samples [series (B)] with the same Fe_xMn_{1-x} layer thickness but opposite layer sequence.

flat interface, as the uncompensated moments cancel out for rough surfaces. One approach to explain the decrease in the ordering temperature for half-integer-filled monolayers was the lower coupling strength between FM and AFM layers due to this canceling of uncompensated spins.

To check this, Fe_xMn_{1-x} layers with integer and half-integer film thicknesses were prepared in series (A). As Fe_xMn_{1-x} grows layer by layer on Cu(001), the roughness of the half-integer-filled layers is higher than that of the integer-filled ones.[14] The half-integer layer filling does not lead to a lower ordering temperature as can be seen in Fig. 2. Therefore the ordering temperature is not this easily related to the roughness of the interface. Either not only the uncompensated spins at the interface might be involved in the coupling or the 3Q spin structure could be distorted at the interface. Another possible explanation is that the FM-AFM coupling is influenced by the different layer filling but does not affect the ordering temperature, or that domains are created in the AFM, which result in compensated spin components.

To survey the dependence on T_{AFM} on the layer filling, samples from series (B) with different layer sequence were investigated. As Ni grows only up to about 6 ML in a layer-by-layer mode on Cu(001),[15] the interface will be much rougher for $Fe_xMn_{1-x}/Ni/Cu(001)$ bilayers than for $Ni/Fe_xMn_{1-x}/Cu(001)$. Figure 3 shows that no difference in T_{AFM} could be observed. Additionally some of the $Fe_xMn_{1-x}/Ni/Cu(001)$ bilayers from series (B) were prepared with an annealed Ni layer (450 K for 20 min.) to smoothen the surface of the Ni layer so that the roughness at the interface is reduced. Also for these samples no difference in the ordering temperature could be observed. This finally clarifies that T_{AFM} is neither influenced by the layer sequence nor by the interface roughness. Note that the temperature readings for series (B) probably are offset by ≈ 40 K with respect to series (A) due to a different temperature sensor mounting.

In summary sample series (A) shows us that T_{AFM} does not depend on the small change in roughness due to integer- or half-integer Fe_xMn_{1-x} film thickness. Sample series (B) shows that T_{AFM} does neither depend on the interface roughness nor on the layer sequence.

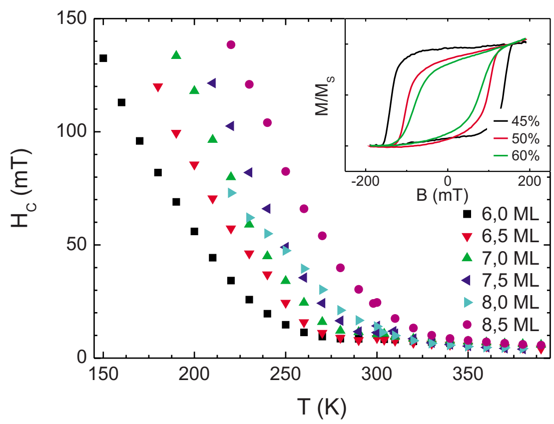

FIG. 4. (Color online) Temperature-dependent coercivities of series (A) samples with $x=50$ at. % Fe. Inset: Fe-concentration-dependent hysteresis curves of the same three 15 ML Ni/6.5 ML Fe_xMn_{1-x}/Cu(001) samples as in Fig. 1 measured at 190 K.

C. Magnetic coupling

While the ordering temperature is found to be independent of both Fe concentration and interface roughness, as discussed in the previous sections, the situation is different for the magnetic coupling strength between FM and AFM layer, as will be shown in this section. In Fig. 1 for series (A) samples one can not only see that the ordering temperature is independent of the concentration but also that the concentration has an influence on the coercivity at low temperatures: The smaller the Fe concentration the steeper the increase in H_C with decreasing temperatures. This becomes clear from the inset of Fig. 4 which shows the hysteresis curves of measurements at 190 K for three samples with different Fe concentration. For 45 at. % Fe the coercivity is higher and the hysteresis loop more squarelike than for a higher Fe concentration. This squareness of the hysteresis curve shows that the magnetization switches almost simultaneously in the whole sample while for less squarelike curves there is a splitting into domains, therefore the more gradual decrease in M_S during the reversal. From this we conclude that the formation of domains is enhanced for higher Fe concentration in Ni/Fe_xMn_{1-x}/Cu(001) bilayers.

As the ordering temperature T_{AFM} showed up to be independent of the Fe concentration, the coupling of the spins inside the AFM layer seems to be the same for all Fe concentrations. On the other hand the stronger the FM-AFM coupling at the interface the higher the increase in coercivity,[11] so the different coercivities at low temperatures show that the FM-AFM coupling must be higher for smaller Fe concentration. From this we can conclude that the Fe concentration influences the coupling between FM and AFM spins at the interface but this has no significant effect on the coupling of the AFM spins inside Fe_xMn_{1-x}.

By comparing the temperature-dependent coercivities in Fig. 3 [series (B)] we can also derive a dependence of the FM-AFM coupling on the interface roughness: For low temperatures the Ni/Fe_xMn_{1-x}/Cu(001) sample shows a higher coercivity than the Fe_xMn_{1-x}/Ni/Cu(001) sample with the higher interface roughness. As the Fe_xMn_{1-x} layers also have different Fe concentration we have to take this into account but Fig. 1 shows that the sample with lower Fe concentration has the higher coercivity. In Fig. 3 the Fe_xMn_{1-x}/Ni sample has a lower coercivity even though the Fe concentration is lower. So from this we deduce that a high interface roughness leads to a lower FM-AFM coupling although T_{AFM} does not change. However, by comparing the samples of series (A) and (B) we can conclude that the FM-AFM coupling is only lowered for a very high interface roughness: The samples of series (A) do not show different gradients in $H_C(T)$ (see Fig. 4). The curves are only shifted along the temperature axis but do not show a stronger increase in $H_C(T)$ for half-integer-filled monolayers. Obviously the small amount of increased roughness for half-integer filled monolayers is not enough to affect the FM-AFM coupling.

In Sec. III B the effect of the FM-AFM coupling on interface roughness and AFM ordering temperature was discussed. By comparing samples with opposite layer sequence we could now show that indeed the FM-AFM coupling is lower for high interface roughness because uncompensated spins from neighboring layers cancel out in the {100} plane of the 3Q structure.[3] From the discussion in this section we can now state that although the FM-AFM coupling is influenced by interface roughness and Fe concentration in the Fe_xMn_{1-x} layer, it does not have a significant impact on T_{AFM}. Obviously the AFM ordering temperature only depends on the thickness of the Fe_xMn_{1-x} layer and is not influenced by the coupling strength to the adjacent FM layer for the bilayers examined in this paper.

As both Co/Fe_xMn_{1-x}/Cu(001) (Ref. 8) and Co/Ni/Fe_xMn_{1-x}/Cu(001) (Ref. 3) bilayers show that T_{AFM} varies with the Fe concentration, our explanation why the samples in this paper do not show this dependence is because they are magnetized out of plane. One possible reason for this difference could be that the 3Q structure is distorted differently due to the magnetization of the adjacent FM layer, i.e., toward the 1Q structure (collinear spins pointing to opposing out-of-plane directions in alternate layers) for out-of-plane magnetization, and toward the 2Q structure (spins pointing oppositely along face diagonals rotated by 90° in alternate layers) for in-plane magnetization.[13] This difference in spin structure might also be responsible for the unlike correlation of T_{AFM} and the FM-AFM coupling.

Now we suggest that this same distortion of the 3Q structure could be the reason for the change in T_{AFM} when the magnetization switches from out of plane to in plane.[3] The 1Q-structurelike distortion, induced by out-of-plane magnetization of the adjacent FM layer, obviously shows a higher-ordering temperature than the AFM spin structure distorted toward 2Q for the in-plane magnetized FM layer. Note that it has been demonstrated that in both cases the spin structure remains three dimensional and noncollinear[7] but it is not known how much quantitatively this three-dimensional spin structure deviates from a one-dimensional 1Q or two-dimensional 2Q spin structure.

In summary sample series (A) shows that the magnetic FM-AFM coupling increases for decreasing Fe concentration. Sample series (B) shows in addition that the coupling is enhanced for lower interface roughness.

D. Thickness dependence of exchange-biased Fe_xMn_{1-x} layers

The samples of series (C) were used to investigate the Fe_xMn_{1-x} thickness dependence of the coercivity and exchange-bias field in a step-by-step manner taking advantage of the *in situ* UHV MOKE setup. In a first step 15 ML of Ni were evaporated on the Cu(001) crystal. For some samples this Ni layer was then annealed to 450 K for 20 min. After cooling down to almost room temperature the first MOKE curves were taken so that the Ni layer was left with remanent magnetization. Then the first few ML Fe_xMn_{1-x} were evaporated and the second set of MOKE loops were measured. Another Fe_xMn_{1-x} layer of the same Fe concentration was evaporated and a MOKE measurement performed. These steps were carried out several times so that thickness-dependent hysteresis curves were obtained at room temperature. As keeping x constant during coevaporation of Fe and Mn through several deposition steps is a difficult process, the resulting inaccuracy in Fe concentration x is relatively large. Here we show only those measurements in which the scatter in Fe concentration after the several evaporation steps is less than 4 at. % Fe. We can discuss these measurements because the results obtained from this series with respect to the dependence of interface roughness and Fe concentration on magnetic coupling agree very well with those in the previous sections.

To keep the interface as clean as possible we decided to not perform any time-consuming temperature-dependent measurements. Furthermore it would not have been possible to determine the ordering temperature for the thick Fe_xMn_{1-x} films as we did not want to heat the sample to more than 400 K.

The resulting thickness-dependent coercivities and exchange-bias fields are shown in Fig. 5. For thin Fe_xMn_{1-x} layers we see that neither H_C nor H_{EB} changes with respect to the values for the pure Ni film (0 ML Fe_xMn_{1-x}). From Fig. 2 it is known that T_{AFM} is approximately RT for Ni/7.5 ML Fe_xMn_{1-x}/Cu(001), so for thicker Fe_xMn_{1-x} films T_{AFM} is above RT and hence one expects an increase in H_C starting at that thickness. Figure 5 confirms this value, and for more clarity this ordering thickness is marked in the figure as t_{AFM}.

With further increasing the Fe_xMn_{1-x} thickness, the coercivity increases up to a maximum at around 15 ML where the AFM anisotropy becomes significantly large so that exchange bias starts to increase. Only for 33 at. % Fe [asterisks in Fig. 5(a)], the AFM anisotropy remains at small values (no exchange bias is observable) even up to 60 ML Fe_xMn_{1-x} (not shown). As series (A) and (B) did not contain any samples with this Fe concentration and a very low AFM anisotropy explains the zero exchange-bias field and the relatively small coercivities, this sample will not be included in any further consideration in this paper.

For the exchange-biased hysteresis loops in Fig. 5 there is a higher displacement of about 25–30 mT (at around 25 ML Fe_xMn_{1-x}) for 50 at. % Fe (triangles) than for 60 at. % Fe (squares) where the exchange-bias field is only 15–20 mT. From Sec. III C we already know that the FM-AFM coupling is higher for lower Fe concentration. For the exchange-biased samples both H_C and H_{EB} depend on both the FM-AFM coupling and the strength of the AFM anisotropy.

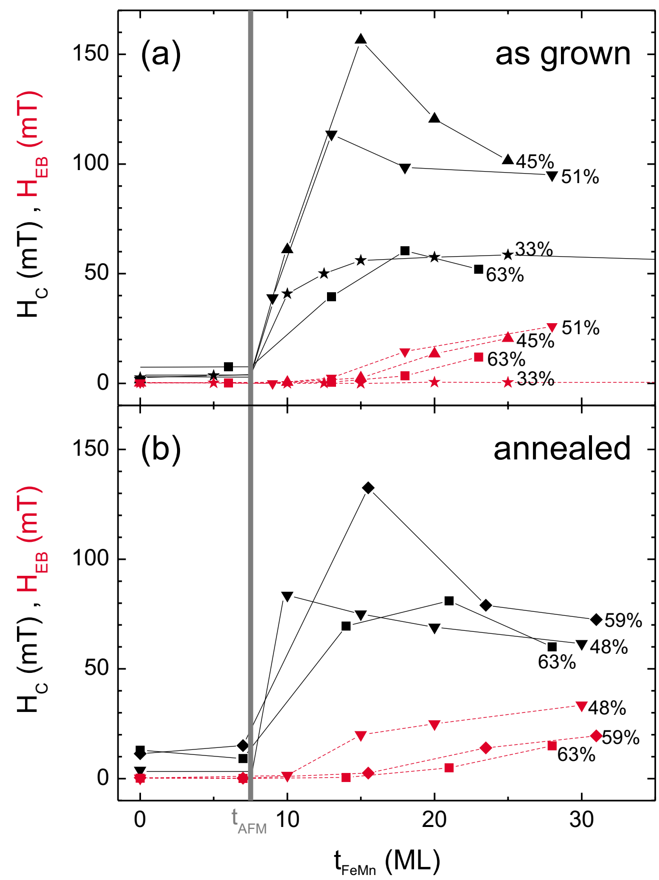

FIG. 5. (Color online) Thickness-dependent coercivities (black, solid lines) and exchange-bias field (red, dashed lines) of t ML Fe_xMn_{1-x} on 15 ML Ni (a) as-grown and (b) Ni layer annealed for 20 min at 450 K [series (C)]. All measurements done at room temperature (300–310 K). Numbers at last data points denote the average Fe content x ($\pm 4\%$) of the Fe_xMn_{1-x} layers. The vertical gray line denotes the thickness at which T_{AFM} equals room temperature. The connection lines are guides to the eye.

Therefore it is hard to decide whether the higher H_{EB} for lower Fe concentration arises from one or the other. Since we have shown in Sec. III C that the FM-AFM coupling is higher for lower Fe concentration, we address the higher displacement for lower Fe concentration to the same phenomenon.

Additionally the magnitude of the exchange-bias field is slightly higher for the annealed samples [Fig. 5(b)] than for the as-grown samples [Fig. 5(a)]. This again agrees with Sec. III C in which a lowered FM-AFM coupling was found for higher interface roughness.

The coercivity shows a different behavior for as-grown and annealed samples. For the as-grown samples in Fig. 5(a) the coercivity is higher for lower Fe concentration. This can be explained by the higher FM-AFM coupling for lower Fe concentration exactly like the higher exchange-bias field. The coercivities of the annealed samples in Fig. 5(b) for 60 at. % Fe are higher than the ones for the as-grown samples (again in accordance to Sec. III C). But then the coercivities for annealed 50 at. % Fe are reduced. Since the FM-AFM coupling is increased for a flat interface, the reduction in coercivity can only be explained by an increased

AFM anisotropy, which leads to a higher exchange-bias field whereas the coercivity goes down.[16] Obviously by annealing the FM film two competing mechanisms are controlled: on one hand the FM-AFM coupling is increased due to the smoother (i.e., less rough) interface, which leads to a higher coercivity. On the other hand the anisotropy of the AFM is also increased but results in a lower coercivity.

In summary the exchange-biased samples [series (C)] show a higher displacement for lower Fe concentration and for lower interface roughness. We address this to the same phenomenon, i.e., the increase in FM-AFM coupling, which we have already shown to be present for series (A) and (B) in Sec. III C. From the reduced coercivity for annealed samples (50 at. % Fe) we conclude that the lower interface roughness leads to an increase in the AFM anisotropy.

IV. SUMMARY

In this systematic investigation on perpendicularly magnetized Ni/Fe_xMn_{1-x} bilayers we could confirm the roughly linear dependence of the ordering temperature T_{AFM} on increasing AFM layer thickness, which can be explained by finite-size effects. However, our studies showed that T_{AFM} does neither depend on the Fe concentration nor on the FM-AFM interface roughness for out-of-plane magnetization.

From the different shapes of the hysteresis curves we could show that the magnetization reversal is more abrupt in Ni/Fe_xMn_{1-x}/Cu(001) bilayers with higher Fe concentration, which could be due to an enhanced formation of domains. Additionally, we could show that the lower the Fe concentration in Fe_xMn_{1-x} $(0.4<x<0.6)$ is, the stronger the FM-AFM coupling will be, as concluded from the coercivity enhancement at low temperatures.

By comparing as-grown and annealed Fe_xMn_{1-x}/Ni/Cu(001) samples we could show that the higher interface roughness in the as-grown samples leads to a lower FM-AFM coupling. This can be explained by a compensation of the otherwise uncompensated spins for rough interfaces. However, Ni/Fe_xMn_{1-x}/Cu(001) bilayers with an integer-filled or half-integer-filled Fe_xMn_{1-x} layer did not show a reduced coupling for the half-integer-filled samples. Obviously the increase in roughness for a half-integer-filled interface is not high enough to result in a reduced FM-AFM coupling.

From the fact that the FM-AFM coupling depends on both the Fe concentration and the interface roughness, but T_{AFM} is independent of these properties, we conclude that the ordering temperature is not influenced by the adjacent FM layer for out-of-plane magnetization in the system studied. We address the difference with respect to in-plane measurements,[3,8] in which T_{AFM} is influenced by the magnetic coupling, to a different distortion of the 3Q spin structure. A rearrangement of the spins toward the 1Q (out-of-plane) or 2Q (in-plane) structure is the probable cause for a modification of the proximity effect at the interface of FM and AFM layers, which leads to the different ordering temperatures. A different magnetic coupling strength between FM and AFM layers, on the other hand, does not lead to a variation in T_{AFM}.

For exchange-biased Fe_xMn_{1-x}/Ni/Cu(001) samples we could show the same behavior: a lower Fe concentration or lower interface roughness leads to an increase in the magnetic coupling and hence to an increased exchange-bias field. Additionally the coercivity reduction for annealed layers at low Fe concentration showed that the annealing of the FM film results in an increase in the AFM anisotropy.

ACKNOWLEDGMENT

This work is supported by DFG under Grant No. KU 1115/9-1.

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