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Exchange coupling between ferro- and antiferromagnetic layers across a non-magnetic interlayer: Co/Cu/FeMn on Cu(001)

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Abstract

The as-grown magnetic domain patterns of epitaxial single-crystalline Co/FeMn bilayers and Co/Cu/FeMn trilayers were investigated by magnetic circular dichroism domain imaging using a photoelectron emission microscope. Small domains were observed when Co was deposited directly on top of antiferromagnetic FeMn films. On inserting a Cu spacer layer between the ferromagnetic Co layer and the antiferromagnetic FeMn layer, the as-grown domain size increases continuously with increasing Cu layer thickness, which is attributed to the decrease of the interlayer exchange coupling between the Co and FeMn layers. Domain images of the Co layer acquired after applying different external magnetic fields confirm the relation between as-grown domain size and interface coupling to the antiferromagnetic FeMn layer across the non-magnetic Cu spacer layer. It is found that a field of 44 Oe is sufficient to annihilate most small domains in the area where Co and FeMn are coupled through the Cu wedge, while it has no effect on the domain configuration of a Co/FeMn bilayer. By analysing the dependence of the average domain size of the Co layer on the Cu thickness in terms of interface coupling between the Co and FeMn layers across the Cu layer, the apparent estimated coupling energy was found to be different for different Co thickness. This is ascribed to kinetic barriers hindering the formation of larger domains from smaller ones.

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1. Introduction

The magnetic coupling between a ferromagnet (FM) and an antiferromagnet (AF) has received much attention in recent years because of its rich physics and the technological importance in magnetoresistive sensors and read heads as well as magnetic random access memory [1]. As a result of the exchange interaction at the interface, the centre of the hysteresis loop of the ferromagnetic layer shifts away from zero along the field axis by an amount called the exchange bias field H_E, accompanied by an enhanced coercivity H_C [2]. Although this phenomenon was observed more than 40 years ago, there are still difficulties in theoretically relating the observed exchange bias field to the actual interface coupling [3–7]. A clear understanding of the underlying principles governing the manifestation of the exchange coupling between antiferromagnetic and ferromagnetic layers is important for understanding various phenomena related to exchange bias.

Another phenomenon that has also attracted attention in the past decade is the long-range magnetic coupling between two ferromagnetic layers across a thin non-magnetic metal interlayer [8–12]. Oscillatory exchange coupling via spacer layers has been established as a general phenomenon for many spacer materials such as 3d, 4d, and 5d non-magnetic transition metals. Recently, several experiments showed that magnetic coupling across non-magnetic (NM) interlayers might also exist in exchange biased systems [13–18]. A pioneering experiment performed by Gökemeijer *et al* indicated that the exchange bias field exhibits an exponential decay with the thickness of the non-magnetic interlayer up to several tens of ångströms [13, 14]. More recently, an oscillation of the exchange bias field as a function of Cu spacer layer thickness was observed in NiFe/Cu/FeMn [15] and NiFe/Cu/NiO [16] structures. Only a few systems have been studied up to now, and it is still not clear whether this interlayer exchange coupling is really a general phenomenon in the biased systems. Actually, opposite results have also been reported [19]. Thomas *et al* found that the exchange bias field in IrMn/NM/CoFe trilayers decreases exponentially with the spacer layer thickness without oscillation, and vanishes for spacer layers thicker than $\approx$10 Å.

Despite these contradictory results concerning the possible presence of an oscillation of the coupling strength, it is safe and reasonable to conclude that the exchange coupling strength between FM and AF layers decreases with increasing spacer layer thickness. This decrease of the coupling energy can be expected to induce some correlated changes in the magnetic domain properties of the FM layer. Hence, the direct visualization of the domain structure in AF/NM/FM trilayer systems can provide useful information relating to how the exchange bias coupling energy varies, locally, with increasing spacer layer thickness. A previous investigation on Co/FeMn bilayers on Cu(001) revealed the presence of small domains in as-grown Co layers on top of antiferromagnetic FeMn layers [20]. This is interpreted as an indication for a random distribution of local uncompensated magnetic moments at the FeMn surface, which spatially fluctuate in direction and size.

This dominant role of the AF domain for the exchange bias coupling has been discussed by Malozemoff in the so-called random field model [4]. Moreover, to quantitatively determine the exchange coupling energy from the observed domain size in the FM layer, the random distribution of AF spins has to be taken into account. Following Malozemoff's work, Zhang *et al* discussed the correlation between exchange bias and the enhancement of the coercivity in exchange bias systems, considering the effect of a random field at the AF surface on the coercivity of the FM film [21]. They predict that the FM domain size L in an exchange coupled FM/AF bilayer is inversely proportional to the exchange coupling energy J_s between the FM and AF layers:

$$L = \frac{zJ_f}{z'J_s}\pi^2 t. \qquad (1)$$

Here t is the thickness of the FM layer, J_s is the average coupling energy between AF and FM spins at the interface, J_f is the exchange energy of the FM, and z and z' are the coordination numbers of atoms in the ferromagnetic layer and at the interface, respectively.

In this paper, we present a microscopic study of single-crystalline Co/Cu/FeMn trilayers by element-resolved magnetic domain imaging using a photoelectron emission microscope (PEEM), which allows one to observe the characteristic changes in the Co domains as a function of Cu film thickness. We show that the typical magnetic domain size in the Co film indeed increases monotonically with increasing the thickness of the Cu spacer layer. An estimate for the interlayer exchange coupling energy between Co and FeMn across the Cu spacer layer according to the above mentioned model leads to an obvious difference in the value between samples with different Co layer thickness. This would be in disagreement with the generally accepted conclusion that the exchange bias is an interfacial effect [7]. In the general picture, the exchange coupling energy should be independent of the ferromagnetic material's thickness if effects due to a change of the Curie temperature T_C of the FM layer can be ignored (a condition which is fulfilled in our experiments). This discrepancy is discussed in terms of kinetic barriers hindering the domains to reach their equilibrium size during deposition of the FM layer.

2. Experiment

The Co/Cu/FeMn trilayers were epitaxially grown on a Cu(001) single-crystal substrate at room temperature by electron beam assisted thermal evaporation. No external magnetic field was applied during evaporation. Single-crystalline fcc FeMn and Co films are obtained due to the low lattice mismatch between FeMn and Cu ($\sim$0.4%) [22], and between FeMn and the in-plane lattice spacing of ultrathin Co films on Cu(001) [23]. LEED images showed a sharp (1×1) pattern even for FeMn film thicknesses of 26 atomic monolayers (ML) [22]. Previous scanning tunnelling microscopy experiments found that the surface of $Fe_{50}Mn_{50}$ films with thicknesses above 10 ML on Cu(001) reveals atomically flat terraces (typically larger than 100 nm) with islands or holes of monatomic height (0.18 nm) [24]. Since the samples presented here were prepared under identical experimental conditions, we believe that this is true also for our samples. The only question is the additional roughness at the Cu/Co interface induced by the Cu interlayer. Although we have no direct data about the roughness of the Cu layer, we can still give a rough estimate. References [25, 26] have reported an rms roughness of about 4 Å for a Cu layer of several nanometres on top of Si(100) deposited by dc magnetron sputtering. Considering the lower thickness and growth rate and the better vacuum during epitaxial deposition in our experiment, the interface roughness should be far below this value.

$Fe_{50}Mn_{50}$ films were obtained by co-evaporation of Fe and Mn from two different sources. Film thicknesses were calibrated by oscillations of the diffracted medium energy electron intensity during evaporation. The systematic error of the cited thickness is about 10% for FeMn and Co, and 20% for Cu. However, the accuracy of the relative thickness within the same sample is about 1%. The chemical composition and growth of the films were investigated by Auger electron spectroscopy. We could not detect surface contamination or surface segregation of one of the chemical species in the FeMn films within the accuracy of the LMM AES peak detection [27]. Thamankar *et al*, measuring the more surface sensitive MVV Auger electrons for different emission angles, reported a small surface segregation of Fe in $Fe_{50}Mn_{50}$/Cu(001), which corresponded to 62% Fe concentration in the topmost layer of 2.8 and 7.3 ML films [28]. The Co layer was grown as continuous films while the Cu film was shaped into a wedge as described in a previous publication [29]. The FeMn layer was either a continuous film or a wedge oriented perpendicularly to the Cu wedge. The Fe and Mn evaporators were carefully

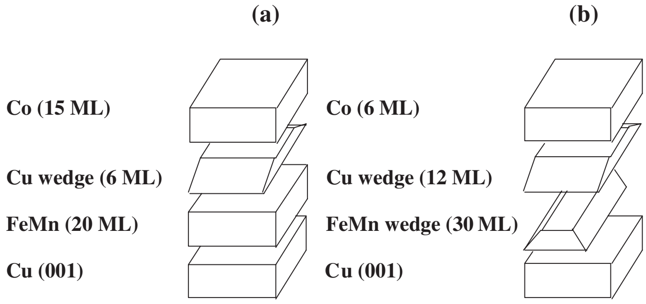

Figure 1. Schematic drawing of the two samples, epitaxial Co/Cu/FeMn trilayers on Cu(001). Sample 1 consists of a single Cu wedge sandwiched between FeMn and Co layers; sample 2 is a crossed FeMn/Cu double wedge covered by a Co layer.

aligned in the axis along the slit and aim at the same point at the substrate, which made the composition error within the wedge smaller than 10% except for the very lowest FeMn thickness. This deviation just causes a small change of the Néel temperature or of the transition thickness from paramagnetism to antiferromagnetism at fixed temperature of the FeMn layer in sample 2 [22], and does not affect the analysis of the domains and their relationship to the coupling. The width of the Cu wedges was about 80 μm, and that of the FeMn wedge 155 μm, both of which are still larger than the average terrace width and the magnetic length scale. Circularly polarized x-rays from the helical undulator beamline UE56/2-PGM2 of BESSY in Berlin were used for illumination, incident to the sample under an angle of 60° from the surface normal. The lateral resolution and field of view in the PEEM were set to 400 nm and 90 μm, respectively. The detailed description of the setup and operation of this PEEM can be found in an earlier paper [30]. Magnetic domain images are presented as the asymmetry of images acquired with positive and negative helicity of the exciting radiation, utilizing the effect of x-ray magnetic circular dichroism (XMCD). In this paper, two samples were investigated, which are schematically shown in figure 1. Sample 1 consists of 20 ML of FeMn, a 0–6 ML Cu spacer layer wedge, and 15 ML Co. Sample 2 was a crossed wedge with 0–30 ML FeMn, 0–12 ML Co, and 6 ML Cu.

3. Results

Figure 2(a) shows an as-grown Co domain image of sample 1. The thickness of the Cu wedge varies from 0 to 6 ML from bottom to top. Unfortunately it is difficult to locate the beginning of the Cu wedge very accurately by acquiring absorption images of metallic Cu due to its relatively long inelastic mean free path and low absorption white line. However, we can get this information indirectly from the behaviour of the Co domain pattern. In figure 2(a), one observes a gradual increase in Co domain size starting at the position labelled '0' on the left axis. Quantitative analysis of the average domain size D was achieved by counting the number of successive bright to dark regions per unit length using line scans along the horizontal direction of figure 2(a). It was found that the observed magnetic domain pattern has a preferential orientation. We can speculate that the origin of this anisotropy in the domain shape could be a preferential substrate terrace direction, which may be caused by Ar^+ ion sputtering during cleaning the substrate. To account for the anisotropic elongated shape of the domains, the domain width obtained by this counting procedure was multiplied by a factor of 1.9. This correction factor was obtained by comparing the square root of the average domain size outside the wedge with the average domain width obtained from horizontal line scans,

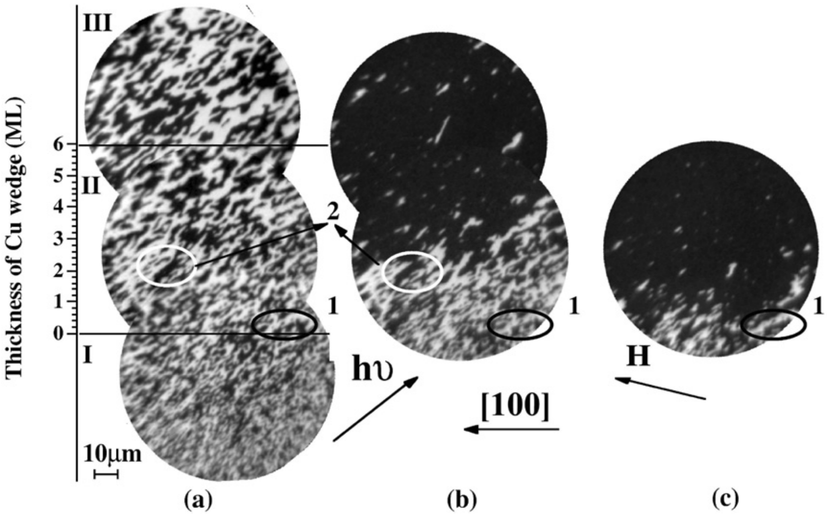

Figure 2. (a) As-grown Co domain image of 15 ML Co/Cu wedge/20 ML FeMn/Cu(001). The Cu thickness increases from bottom to top, as indicated at the left axis. The thickness of the platform of the Cu wedge is 6 ML. ((b), (c)) Co domain images of the same area of the sample after application of an external field of 66 Oe (b) and 88 Oe (c) in the direction indicated by H.

and is applied to yield the geometric average of the long and short side of the domains as our resulting domain size. This domain size is shown in figure 4(a) by solid symbols as a function of position along the direction of the Cu wedge. The straight solid line serves as a guide to the eye. The start and end of the wedge were determined from the positions where the Co domain size starts to deviate from being constant, labelled 0 and 6 ML at the bottom axis of figure 4(a), as well as on the left axis of figure 2. Three regions labelled as I, II, and III in figure 2 correspond to regions on the sample where no Cu, a Cu spacer layer with increasing thickness, and a Cu spacer layer with 6 ML constant thickness are present, respectively. The analysis shows that the average domain size stays nearly constant with a value of $D \approx 7.1\ \mu$m in area I. Direct exchange interaction between the Co layer and fluctuating uncompensated magnetic moments, 'domains' in the FeMn layer, induces replicated small domains in the Co layer during the early stages of Co growth, which partly merge together to reach the finally observed domain size when the Co layer becomes thicker [20]. In region II, the domains in the Co layer become bigger with increasing thickness of the Cu spacer layer. The size arrives at $D \approx 11.8\ \mu$m and stays constant at this value in region III. In other words, the as-grown Co domain size increases when inserting a Cu spacer layer with increasing thickness.

We also acquired domain images after application of different external magnetic fields. It is found that a saturated domain with black contrast, the magnetization direction of which corresponds to the direction of the applied field, first appears in regions III and II. With increasing external field, this black region expands along the Cu wedge from thicker to thinner Cu thicknesses. Figure 2(b) shows the Co domain pattern after application of a 33 Oe external magnetic field at room temperature in the direction indicated by H, and figure 2(c) after 44 Oe in the same direction. Note the labels 1 and 2, which indicate identical positions in images (a), (b), and (c). It is seen that after application of 44 Oe, the saturated black area has already extended to the edge of region I, i.e., close to the beginning of the wedge. The motion of the border of the black domain with increasing applied field confirms the decay of the exchange coupling strength along the wedge [31]. Actually, a weaker pinning strength between Co and

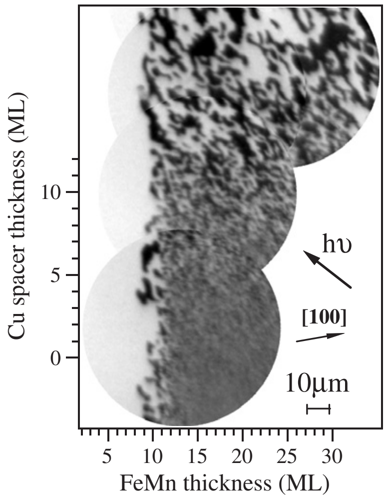

Figure 3. As-grown Co domain image of 6 ML Co/Cu wedge/FeMn wedge/Cu(001). The Cu thickness increases from bottom to top, as indicated at the left axis, the FeMn thickness from left to right, as indicated at the bottom axis. The thickness of the platform of the Cu wedge is 12 ML.

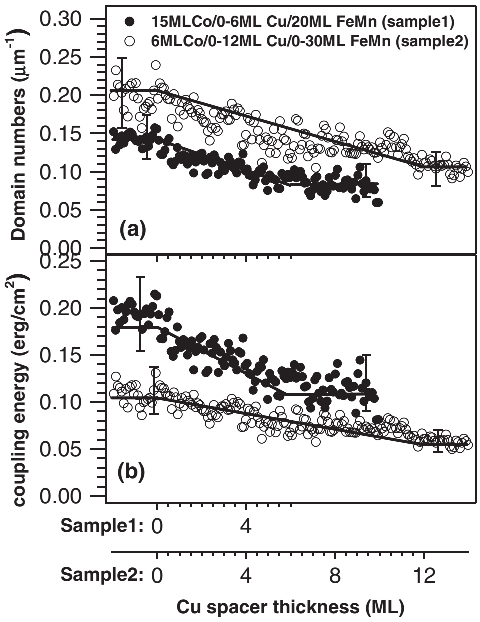

Figure 4. (a) The average domain size determined from the as-grown Co domain images as a function of the Cu spacer thickness. (b) The exchange coupling energy J_s obtained using equation (1) as a function of the Cu spacer thickness. Solid symbols are for sample 1 and open symbols for sample 2. The Cu layer thicknesses for both samples are indicated at the bottom axis. The straight solid lines are guides to the eye, and represent the shape and position of the Cu wedges. The error bars represent the statistical error from the domain counting.

FeMn results in a lower coercivity, and an easier magnetic saturation of the Co layer. Finally, it is found that the domain pattern in area I remains unchanged even after the application of a field of 300 Oe. The small value of the magnetic field needed to saturate the Co films pinned by FeMn across a Cu spacer indicates that the exchange interaction across the Cu layer is much weaker compared to the case with no Cu spacer layer. It is worthwhile pointing out that only local exchange bias may exist in our samples since no magnetic field was applied during growth, which results in the absence of macroscopic exchange bias [22, 32].

Figure 3 shows the as-grown domain pattern of sample 2 with a thicker Cu wedge, varying in thickness from 0 to 12 ML, sandwiched between 6 ML Co and a 0–30 ML FeMn wedge. The FeMn thickness increases from left to right, as indicated at the bottom axis. At FeMn thicknesses below 10 ML a single big white domain is seen in the Co domain image. From previous experiments it is known that at these low thicknesses FeMn is not antiferromagnetic at room temperature [22]. The Co layer exhibits small domains at higher FeMn thicknesses, the size of which depends on the position along the Cu wedge. No influence of the FeMn thickness on the as-grown Co domain size is observed except in the close vicinity of the transition region around 10 ML FeMn thickness. This is due to the interface properties of exchange bias, i.e., only spins near the interface between antiferromagnetic and ferromagnetic layers can contribute to the exchange coupling. In our case, an interface area depth of 3 ML in the FeMn layer can be concluded from figure 3.

The exact location of the Cu wedge is again determined from the analysis of the average Co domain size as described above as a function of position along the wedge as shown in figure 4(a) by open symbols. The resulting Cu thickness is labelled at the bottom of figure 4(a), and at the left axis of figure 3. Note that the lengths of the Cu wedges in both samples are the same, but are scaled in figure 4(a) in order to facilitate comparison of the data for identical Cu thicknesses. It is found that the domain size in sample 2 increases from $D \approx 4.9$ to 9.5 μm along the length of the Cu wedge. It shows a behaviour similar to the 6 ML thick Cu wedge, i.e., an increase of the domain size with increasing Cu thickness, followed by a region of approximately constant value, which corresponds to the platform of the Cu wedge.

4. Discussion

It is generally accepted that the strength of the exchange coupling between the ferromagnetic and antiferromagnetic layers decreases with increasing spacer layer thickness. Thus we conclude that the observed change in domain size in each of the two samples is related to the decrease of the AF/FM exchange coupling strength across the Cu spacer layer. In addition, the domain size is found to be about 50% larger for identical Cu thicknesses in sample 1 (15 ML Co) compared to sample 2 (6 ML Co). This is a consequence of the competition between domain wall energy in the Co film, which increases per unit area with increasing Co film thickness, and the coupling to domains at the surface of the FeMn layer, which is independent of Co thickness.

Both effects are included in the model of Zhang *et al* [21]. To test its validity in the present case, we apply equation (1) to our data to extract an exchange coupling energy. Figure 4(b) gives the relationship between the estimated exchange coupling energy J_s and the Cu thickness for both samples. The solid symbols give the result for sample 1, the open symbols for sample 2. The straight solid lines are guides to the eye. For the calculation, the exchange constant of fcc Co $J_f = 17.3$ erg cm^{-2} [33], the monolayer thickness $a_0 = 1.78$ Å, and $z = 12$, $z' = 4$ were used. In the limit of direct coupling ($d_{Cu} = 0$), J_s results as $\approx$0.19 erg cm^{-2} for sample 1 (15 ML Co/Cu/FeMn), and $\approx$0.11 erg cm^{-2} for sample 2 (6 ML Co/Cu/FeMn), which are consistent with the values of interface coupling energies listed in [7] for polycrystalline FeMn films, but exceed those for (100) textured samples. However, it is worthwhile pointing out that the values in [7] are estimated from the exchange bias field. We observe exchange bias at room temperature in our single-crystalline samples only at FeMn thicknesses greater than 20 ML [22]. As reported in our previous publication, [20], we have estimated an interface coupling energy of 0.2 erg cm^{-2} for an epitaxial single-crystalline 15 ML Co/FeMn bilayer on Cu(001), in which there is also actually zero exchange bias at room temperature, by considering the competition between the interface exchange coupling and the magnetic anisotropy energy of Co.

It is worthwhile further comparing our results with the interlayer exchange coupling energy for two coupled FM layers across a paramagnetic spacer layer. Heinrich *et al* [34] have measured the coupling strength in a 9.4 ML Fe/12 ML Cu/16 ML Fe trilayer by ferromagnetic resonance. They give a value of ~ -0.294 ergs cm^{-2}. Zhang *et al* report a value of $\sim$0.14 ergs cm^{-2} for 32 Å Co/20 Å Ru/32 Å Co [35], and Lindner *et al* obtain $\sim$0.02 ergs cm^{-2} in 7 ML Ni/9 ML Cu/2 ML Co [36]. These values are significantly higher than the coupling we find for 6 ML Co/12 ML Cu/30 ML FeMn, namely 0.06 ergs cm^{-2}, except for the one of Ni/Cu/Co which has a lower value. One has to keep in mind, however, that the interlayer coupling between two ferromagnetic layers is principally different from the situation investigated here. While at the interface of an FM layer every atom contributes equally to the coupling, the interface of an AF layer comprises atoms of opposite spin directions, either because the antiferromagnetic spin structure leads to a cancellation of magnetic moments in the interface plane (so-called compensated AF interfaces), or due to monatomic steps at the interface in the case of so-called uncompensated AF interfaces. This is the reason that the direct coupling at the AF/FM interface is already orders of magnitude lower than that between two ferromagnetic layers in direct contact. From previous experiments at FM/FeMn/FM trilayers we know that the FeMn(001) interface belongs to the compensated AF interfaces [37].

Recently, Thamankar *et al* have observed an Fe surface segregation in FeMn films on Cu(100) [28]. About 0.24 ML of excess Fe atoms at the interface were estimated from their experiments. This coincides with the observation of an induced ferromagnetic moment in about 30% of the interface Fe atoms [38]. From our results we cannot decide whether these Fe atoms are important for the interface coupling, i.e., whether the coupling is mainly between FM Fe atoms and the FeMn layer, or directly between Co and FeMn. We can suppose, though, that the coupling between these FM Fe moments at the interface and the FM Co layer is of the same order as that inside the FM layer. This coupling between Co and these small interface net Fe moments may give some small contributions to the splitting of the Co domains, resulting in a small overestimation of the interlayer exchange coupling strength between Co and FeMn.

From the above analysis it would follow that the value of the exchange coupling energy for sample 1 is nearly twice that of sample 2 for the same Cu thickness. However, it is known that the exchange bias coupling strength is independent of the ferromagnetic layer thickness if the effect due to a change of T_C can be ignored. According to Zhang's model, the domain size should be proportional to the FM layer thickness for constant FM/AF coupling; see equation (1). In our samples the domain size is indeed smaller in the sample with smaller Co layer (sample 2), but not by a factor of 2.5, which would be the ratio of the Co layer thicknesses of the two samples. Since the coupling energies were calculated from the observed domain size, this indicates that some effect related to the FM thickness on the domains is not considered in the model we adopted. A possible explanation is that the domain size we observe in the as-grown domain images is not the equilibrium domain size, but smaller. The domain size is expected to be very small during the first stages of deposition of the Co layer, when it is just thick enough to support ferromagnetism at room temperature, at about 2 ML [39]. When the Co film becomes thicker, domains have to merge together in order to form bigger domains. That process may result in metastable states with domains smaller than expected from the energetic minimum configuration. Some small energy barriers connected to the annihilation of domain walls may be the reason for that. Such metastable domain patterns become the more likely the bigger the domains already are, because the energy gain from reducing the total domain wall length is reduced quadratically with domain size. Unfortunately, at this moment, the details of this effect are still unclear. Some indication for such an energy barrier comes from heating Co/FeMn bilayers to a temperature above the antiferromagnetic ordering temperature of the FeMn layer [20]. Although in such a case, from an energetic point of view, the existing small domains should merge into one infinitely large domain, the average domain size does not exceed 20 μm [20]. Another possible reason related to kinetic energy barriers may be the finite size of the wedge. Once the domain size becomes comparable to the wedge dimension, this could lead to a smaller domain size than what would be expected from complete energy minimization. To build a correct relationship between the domain configuration and the exchange coupling between FeMn and Co, this barrier for formation of large domains should be taken into account. The values displayed in figure 4(b) thus represent just an upper bound for the AF/FM coupling across the Cu spacer layer. In the case of sample 2, the domain size for zero Cu layer thickness extracted from the image, figure 3, may be too high, since here the exact analysis of the average domain size is limited by the spatial resolution of the images. Here the resulting exchange coupling energy is therefore possibly underestimated. It is plausible to assume a similar value for $d_{Cu} = 0$ as found in sample 1. Thus a more reliable value of J_S could be determined by this method only when the acquired domain images are well resolved and the energy barrier discussed above is taken into account.

In spite of these uncertainties in the calculated coupling energy, we can still conclude that the exchange coupling strength decreases rapidly with increasing Cu spacer thickness. The rapid reduction of interlayer coupling strength with increasing Cu spacer thickness is similar to the results presented in [13, 14] except for the characteristic decay length. However, unlike the experiments reported in [15, 16], our results do not show an oscillation larger than the error bars, which result from the statistics of counting domains. Some oscillatory-like fluctuations in sample 2 (see figure 4) are smaller than the error bars and should not be taken too seriously because due to counting the same domains over a certain range of the image the apparent statistics seem better than they actually are.

Lin *et al* have proposed a theoretical explanation of the oscillatory exchange coupling in an AF/NM/FM trilayer system [16, 17]. In this explanation, the oscillatory RKKY-like coupling competes temperature dependently with the effective antiferromagnetic coupling within the AF layer, as well as with the dipolar interaction between FeMn and Co. The dominant mechanism controls the characteristic behaviour of the exchange coupling. It is believed that the RKKY-like coupling increases more slowly with decreasing temperature than the other two interactions. Well below the Néel temperature, the dipolar interaction and antiferromagnetic coupling within the FeMn layer are dominant, and the oscillatory behaviour due to the RKKY-like coupling is thus suppressed. This explanation could also be applied to our case, since all our measurements were performed at room temperature, which is well below the Néel temperature of 20 and 30 ML FeMn films (between 480 and 500 K). If the oscillating part is only a small contribution to the coupling energy, and is superimposed on a much more prominent overall decrease with increasing Cu thickness, it may also not be observable in the present experiments. To make a clear conclusion about the oscillating coupling, further careful experiments with a better resolution are probably needed for reducing the error bars. To corroborate the explanation given above, temperature dependent measurements at a different system using an antiferromagnetic layer with a lower Néel temperature would be desirable.

The independence of the average Co domain size on the thickness of the FeMn layer as soon as the latter exceeds 13 ML is an indication that changes of the FeMn spin structure for large FeMn thickness are sufficiently small and probably beyond what we can resolve in this experiment during the formation of the Co domain pattern. With the FeMn layer thickness thinner than 13 ML, a lower apparent coupling energy would be expected due to a weaker antiferromagnetic interaction, and larger Co domains should appear, as we observed in figure 3.

5. Conclusion

In conclusion, by using high quality single-crystalline epitaxial Co/Cu/FeMn trilayers, we show that the as-grown domain size of an FM layer deposited onto an AF layer is an indicator for the coupling strength at the FM/AF interface or across a non-magnetic spacer layer. It is found that the as-grown Co domain size monotonically increases with increasing Cu spacer layer thickness. A model based on the assumption of a random field at the surface of the AF layer proposed by Zhang *et al* [21] reproduces the correlation between coupling strength and FM domain size. Using that model, the observed average Co domain size can be converted into a coupling energy. However, kinetic barriers for the merging of magnetic domains may also play a role in determining the observed Co domain size. Such effects may explain the apparent discrepancy of the AF/FM coupling energy at a certain Cu layer thickness, determined from two samples with different thickness of the Co layer.

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References

[1] Dieny B, Speriosu V S, Parkin S S P, Gurney B A, Wilhoit D R and Mauri D 1991 *Phys. Rev.* B **43** 1297
Kools J C S 1996 *IEEE Trans. Magn.* **32** 3165
[2] Meiklejohn W H and Bean C P 1957 *Phys. Rev.* **105** 904
[3] Mauri D, Siegmann H C, Bagus P S and Kay E 1987 *J. Appl. Phys.* **62** 3047
[4] Malozemoff A P 1987 *Phys. Rev.* B **35** 3679
[5] Koon N C 1997 *Phys. Rev. Lett.* **78** 4865
[6] Stiles M D and McMichael R D 1999 *Phys. Rev.* B **59** 3722
[7] For a recent review, see Nogues J and Schuller I K 1999 *J. Magn. Magn. Mater.* **192** 203
[8] Parkin S S P, More N and Roche K P 1999 *Phys. Rev. Lett.* **64** 2304
[9] Wang Y, Levy P M and Fry J L 1999 *Phys. Rev. Lett.* **65** 2732
[10] Parkin S S, Bhadra R and Roche K P 1991 *Phys. Rev. Lett.* **66** 2152
[11] Baltensperger W and Helman J S 1990 *Appl. Phys. Lett.* **57** 2954
[12] Bruno P and Chappert C 1991 *Phys. Rev. Lett.* **67** 1602
[13] Gökemeijer N J, Ambrose T and Chien C L 1997 *Phys. Rev. Lett.* **79** 4270
[14] Gökemeijer N J, Ambrose T, Chien C L, Wang N and Fung K K 1997 *J. Appl. Phys.* **81** 4999
[15] Mewes T, Roos B F P, Demokritov S O and Hillebrands B 2000 *J. Appl. Phys.* **87** 5064
[16] Lin M-T, Ho C H, Chang C-R and Yao Y D 2001 *Phys. Rev.* B **63** 100404 R
[17] Lee Y-J, Chang C-R, Hong T-M, Ho C H and Lin M-T 2002 *J. Magn. Magn. Mater.* **239** 57
[18] Gruyters M, Gierlings M and Riegel D 2001 *Phys. Rev.* B **64** 132401
[19] Thomas L, Kellock A J and Parkin S S P 2000 *J. Appl. Phys.* **87** 5061
[20] Kuch W, Offi F, Chelaru L I, Kotsugi M, Fukumoto K and Kirschner J 2002 *Phys. Rev.* B **65** 140408R
[21] Zhang S, Dimitrov D V, Hadjipanayis G C, Cai J W and Chien C L 1999 *J. Magn. Magn. Mater.* **198/199** 468
[22] Offi F, Kuch W and Kirschner J 2002 *Phys. Rev.* B **66** 064419
[23] Cerdá J R, De Andres P L, Cebollada A, Miranda R, Navas E, Schuster P, Schneider C M and Kirschner J 1993 *J. Phys.: Condens. Matter* **5** 2055
[24] Kuch W, Chelaru L I and Kirschner J 2004 *Surf. Sci.* **566–568** 221
[25] Liu C, Yu C, Jiang H, Shen L, Alexander C and Mankey G J 2000 *J. Appl. Phys.* **87** 6644
[26] Pakala M, Huai Y, Anderson G and Miloslavsky L 2000 *J. Appl. Phys.* **87** 6653
[27] Offi F 2002 *PhD Thesis* Martin-Luther-University Halle–Wittenberg (http://sundoc.bibliothek.uni-halle.de/diss-online/02/02H126/)
[28] Thamankar R, Bhagwat S and Schumann F O 2004 *Phys. Rev.* B **69** 054411
[29] Kuch W, Gilles J, Offi F, Kang S S, Imada S, Suga S and Kirschner J 2000 *J. Electron Spectrosc. Relat. Phenom.* **109** 249
[30] Kuch W, Frömter R, Gilles J, Hartmann D, Ziethen Ch, Schneider C M, Schönhense G, Swiech W and Kirschner J 1998 *Surf. Rev. Lett.* **5** 1241
[31] Wang J, Kuch W, Offi F, Chelaru L I, Kotsugi M and Kirschner J 2004 *J. Appl. Phys.* **95** 7504
[32] Offi F, Kuch W, Chelaru L I, Kotsugi M and Kirschner J 2003 *J. Magn. Magn. Mater.* **261** L1–L6
[33] Tannenwald P E and Weber R 1961 *Phys. Rev.* **121** 715
[34] Heinrich B, Celinski Z, Cochran J F, Arrott A S, Myrtle K and Purcell S T 1993 *Phys. Rev.* B **47** 5077
[35] Zhang Z, Zhou L, Wigen P E and Ounadjela K 1994 *Phys. Rev. Lett.* **73** 336
[36] Lindner J, Rüdt C, Kosubek E, Poulopoulos P, Baberschke K, Blomquist P, Wäppling R and Mills D L 2002 *Phys. Rev. Lett.* **88** 167206
[37] Kuch W, Chelaru L I, Offi F, Wang J, Kotsugi M and Kirschner J 2004 *Phys. Rev. Lett.* **92** 017201
[38] Offi F, Kuch W, Chelaru L I, Fukumoto K, Kotsugi M and Kirschner J 2003 *Phys. Rev.* B **67** 094419
[39] Schneider C M, Bressler P, Schuster P, Kirschner J, de Miguel J J and Miranda R 1990 *Phys. Rev. Lett.* **64** 1059