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Magnetic domain investigation in Co/Cu/FeMn trilayers

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The magnetic domain patterns of epitaxial single-crystalline Co/FeMn bilayers and Co/Cu/FeMn trilayers were investigated by magnetic circular dichroism domain imaging using photoelectron emission microscopy. The as-grown domain size increases continuously with increasing Cu layer thickness, which is attributed to the decrease of the interlayer exchange coupling between ferromagnetic Co and antiferromagnetic FeMn layers. Domain images of the Co layer acquired after applying different external magnetic fields show a decrease in coercivity with increasing Cu layer thickness, confirming the reduction of magnetic coupling energy with increasing Cu thickness. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1669123]

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 data storage industry,[1,2] in particular in magnetoresistive sensors and read heads as well as for magnetic random access memory devices. Although the effect of exchange bias, a unidirectional magnetic anisotropy in AF/FM bilayers, was observed more than 40 yr ago, there are still difficulties in theoretically relating the observed exchange bias field to the actual interface coupling.[3–7] However, a clear understanding of the underlying principles governing the manifestation of the exchange coupling between antiferromagnetic and ferromagnetic layers is important to understand various phenomena related to exchange bias. On the other hand, oscillatory interlayer exchange coupling between two ferromagnetic layers via spacer layers has been established, in the past decade,[8–12] as a general phenomenon for many spacer materials such as $3d$, $4d$, and $5d$ nonmagnetic transition metals. Recently, several experiments showed that magnetic coupling across nonmagnetic interlayers might also exist in exchange biased systems.[13–17] A pioneering experiment performed by Gökemeijer *et al.* indicated that the exchange bias field exhibits an exponential decay with the interlayer thickness up to several tens of angstroms.[13,14] More recently, an oscillation of the long-range exchange bias field 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. 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 ~10 Å.[18]

In this article, we present an x-ray magnetic circular dichroism photoelectron emission microscopy (XMCD-PEEM) study of single-crystalline Co/Cu/FeMn trilayers. The Co domain patterns after applying different external magnetic fields were recorded in order to investigate the influence of the spacer layer thickness on the exchange bias coupling and the coercivity. We had observed previously that very small domains are found in as-grown Co/FeMn bilayers, which are the result of randomly fluctuating magnetic pinning experienced by the growing Co layer at the surface of the AF FeMn layer.[19] We show here that the typical magnetic domain size in the as-grown Co film on top of Cu/FeMn increases monotonically with increasing thickness of the Cu spacer layer, which implies that the exchange coupling between Co and FeMn layers decreases with increasing Cu thickness. It is found that by applying external magnetic fields a saturated area expands along the Cu wedge from thicker to thinner Cu thickness with increasing external field strength, which indicates that the coercivity of the trilayers increases with decreasing Cu spacer thickness. It is also found that the coercivity approximately scales with the inverse Co thickness, as it was also found for Co/FeMn bilayers.[20]

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. $Fe_{50}Mn_{50}$ films were obtained by coevaporation of Fe and Mn from two different sources. Film thicknesses were calibrated by oscillations of the diffracted medium energy electron intensity during evaporation.[20] 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%. Chemical composition and growth of

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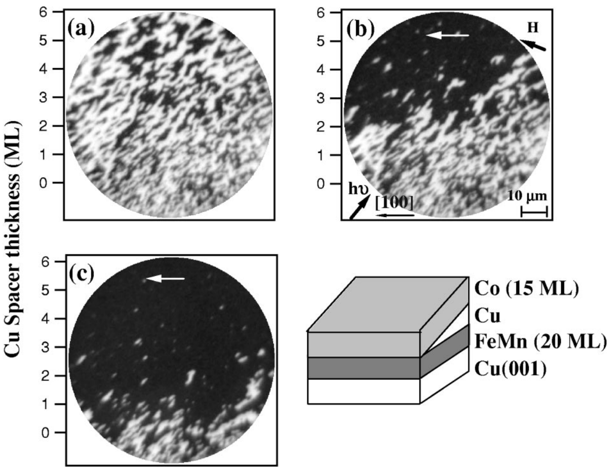

FIG. 1. (a) As-grown Co domain image of 15 ML Co/Cu wedge/20 ML FeMn/Cu(001). The Cu thickness increases from bottom to top, as indicated at the left axis. The thickness of the platform of the Cu wedge is 6 ML. (b), (c) Co domain images of the same area of the sample after application of an external field of 33 Oe (b) and 44 Oe (c) in the direction indicated by *H*. The arrows in the domain indicate the magnetization direction.

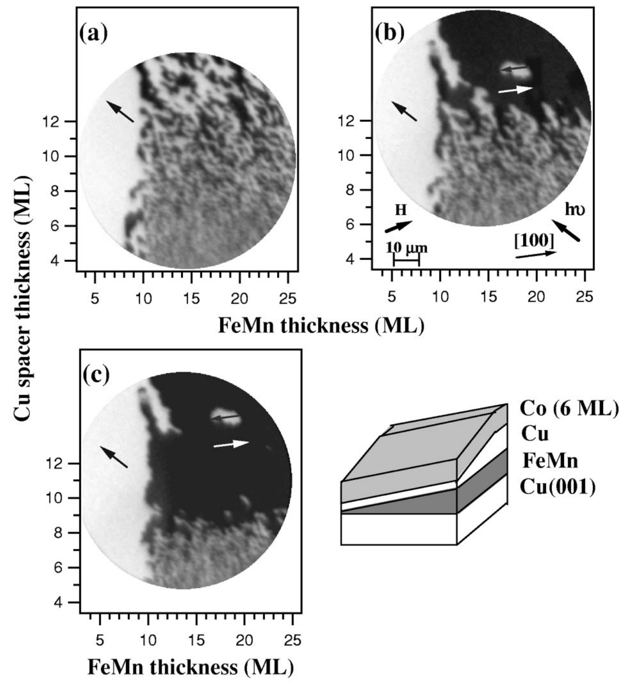

FIG. 2. (a) As-grown Co domain image of 6 ML Co/Cu wedge/FeMn wedge/Cu(001). The Cu thickness increases from bottom to top, as indicated at the left axis, the FeMn thickness from left to right, as indicated at the bottom axis. The thickness of the platform of the Cu wedge is 12 ML. (b), (c) Co domain images of the same area of the sample after application of an external field of 33 Oe (b) and 55 Oe (c) in the direction indicated by *H*. The arrows in the domains indicate the local magnetization direction.

the films were investigated by Auger electron spectroscopy. The Co layer was grown as a continuous film while the Cu film was shaped into a wedge as described in a previous publication.[21] The FeMn layer was either a continuous film or a wedge oriented perpendicularly to the Cu wedge. The width of the Cu wedges was about 80 μm, that of the FeMn wedge 155 μm. Circularly polarized x rays from the helical undulator beamline of the Max Planck Society (UE56-2 PGM2) at BESSY in Berlin were used, incident to the sample under an angle of 60° from the surface normal. The lateral resolution and field of view were set to 400 nm and 90 μm, respectively. A detailed description of the setup and operation of this PEEM can be found in an earlier paper.[22] The magnetic domain images were constructed by taking the intensity asymmetry of images acquired with positive and negative helicity of the exciting radiation, utilizing the effect of XMCD. The external magnetic field was applied along a direction inclined from [100] by 22° for sample 1, and 15° for sample 2. In this article, two samples were investigated: sample 1 consists of 20 atomic monolayers (ML) of FeMn, a 0–6 ML Cu spacer layer wedge, and 15 ML Co, and sample 2 was a crossed wedge of 0–30 ML FeMn, 0–12 ML Cu, and 6 ML Co.

Figure 1 shows the selected domain patterns of sample 1 before and after applying external magnetic fields of different strengths. The as-grown domain size increases continuously with increasing Cu layer thickness, which is attributed to the decrease of the interlayer exchange coupling between Co and FeMn layers.[19] It is found that when the external field exceeds 25 Oe, a saturated area with black contrast appears in the upper part of the image where the Cu spacer has a large thickness. The magnetization direction in that domain is along [100]. This area expands down to smaller Cu thicknesses after applying external fields at room temperature in the direction indicated by *H* of 33 Oe [Fig. 1(b)] and 44 Oe [Fig. 1(c)]. A similar observation was also made in sample 2 (Fig. 2). One can see from Fig. 2(a) that the Co layer exhibits small domains at higher FeMn thicknesses, while a single large domain is present at FeMn thicknesses below 10 ML. From previous experiments it is known that at a thickness lower than 10 ML FeMn is not antiferromagnetic at room temperature.[19,20] The presence of small domains in as-grown Co layers on top of antiferromagnetic FeMn layers is due to the random distribution of local uncompensated magnetic moments at the FeMn surface, which spatially fluctuate in direction and size.[19] 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. After application of an external magnetic field, a saturated domain with a magnetization direction along [100] (black contrast) appears in the upper right region of the image. The quantitative analysis of the contrast of this domain shows that the magnetization direction changes from [110] to [100] with increasing FeMn thickness from below 10 ML to above. It is known that the easy axis of thin fcc Co films is along ⟨110⟩. We have reported recently that the easy axis of ultrathin Co films changes from ⟨110⟩ to ⟨010⟩ when coupled to an antiferromagnetic FeMn film.[19] Thus we can conclude that the exchange coupling between the Co and FeMn layer exists even across a Cu spacer of at least 12 ML.

It is also found that the saturated region in the Co layer expands along the Cu wedge with increasing external field, while the magnetization direction remains unchanged. Figure 2(b) shows the Co domain pattern of sample 2 after the application of a 33 Oe external magnetic field at room temperature in the direction indicated by *H* [Fig. 2(c)] after 55 Oe in the same direction. Comparing Figs. 2(b) and 2(c) to Fig. 1,

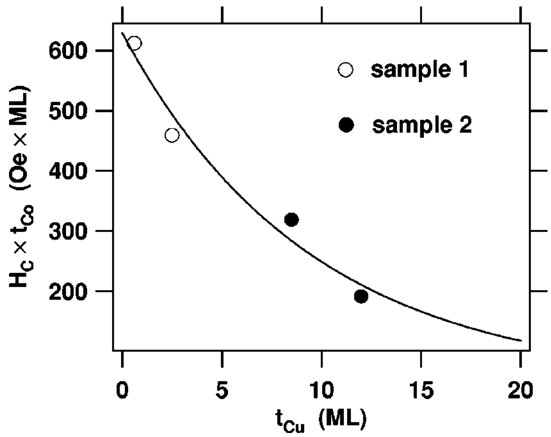

FIG. 3. The product of the coercivity and the Co layer thickness as a function of the Cu spacer layer thickness. The line is an exponential fit to the data.

it is seen that after application of 44 Oe, the saturated black area in sample 1 has already extended to almost the beginning of the Cu wedge (0.5 ML Cu thickness). However, in sample 2, a field of 55 Oe only saturates the Co film up to the region where the Cu thickness is higher than 8.5 ML, as shown in Fig. 2(c). Since a weaker pinning strength between Co and FeMn results in a lower coercivity, and an easier magnetic saturation of the Co layer, the motion of the border of the saturated area with increasing applied field confirms the decay of the exchange coupling strength along the wedge, i.e., the exchange coupling strength across the Cu spacer decreases with increasing Cu thickness. The low 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.

Several explanations for the coercivity enhancement in exchange bias systems have been presented, based on experimental and theoretical investigations. What has become clear due to the recent work is that the reversal of the FM layer is not simply due to coherent rotation on both sides of the loop and relies on a realistic description of the reversal mechanism.[23,24] A common feature in all models presented is that the FM layer thickness dependence of the coercivity is very sensitive to the coercive mechanism at work. It has often been observed that the coercivity varies as $H_C \propto 1/t_F$, where t_F is the thickness of the FM layer. Such an inverse proportionality has also been observed in our previous surface magneto optic kerr effects experiments of Co/FeMn bilayers.[20] To compare the two samples with different Co thicknesses, we plotted the product of H_C and Co thickness as a function of Cu thickness in Fig. 3, where the coercivity was estimated as the projection of the external field along the easy axis. We find that the coercivity, scaled by the inverse Co layer thickness, decreases drastically with increasing Cu thickness, which indicates that the interaction between FeMn and Co decreases very quickly with increasing Cu spacer thickness. Under the assumption that the exchange coupling across the Cu spacer layer is still strong enough to validate the scaling by the inverse Co thickness, one can see that the coercivity of the trilayers approximately follows an exponential decay with a decay length of ~9.4 ML. In spite of the uncertainties in the fitting due to insufficient data, we can still conclude that the decay length of the coercivity in our sample is much longer than the decay length of exchange bias field across a Cu spacer layer reported in the literature.[13–17] In Ref. 13, an exponential decay with a length of 4.1 Å has been reported. However, the behavior of the coercivity may be different than that of the exchange bias field, since they are not necessarily proportional to each other.

In conclusion, by studing domain images of single-crystalline epitaxial Co/Cu/FeMn trilayers, we show that the trilayers can be progressively saturated by applying external magnetic fields of increasing strength, which indicates a decrease of the interlayer exchange coupling between Co and FeMn layers across the nonmagnetic Cu spacer with increasing Cu thickness. The dependence of the coercivity, scaled by the inverse Co layer thickness on the Cu thickness, further confirms the attenuating effect of the Cu spacer on the coupling between Co and FeMn layers.

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