Uncompensated spins in a micro-patterned CoFeB/MnIr exchange bias system

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The element specific domain configuration of a microstructured $Co_{86}Fe_{10}B_4/Mn_{77}Ir_{23}/Ni_{80}Fe_{20}/Si_3N_4$ exchange bias film was studied by photoemission electron microscopy using x-ray magnetic circular dichroism. In the dots the magnetization shows less preferred orientation along the exchange bias direction than in unstructured areas. Uncompensated Mn spins at the CoFeB/MnIr interface with an antiferromagnetic coupling between the Mn and the Co magnetic moments could be studied by imaging and spectromicroscopy. © *2004 American Institute of Physics*.
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Exchange bias, i.e., a horizontal shift of the hysteresis loop by a value H_{eb} arises when a system with a ferromagnet (F)/antiferromagnet (AF) interface is cooled or grown in a static magnetic field below the Néel temperature of the AF.[1] Extensive research has led to the assumption that this technologically important effect originates in uncompensated and pinned magnetic moments of the AF.[2] Typically H_{eb} is negative, i.e., opposite to the direction of the cooling field, however, in some systems, e.g., in Fe/FeF_2 or Fe/MnF_2 a positive shift of the hysteresis loop has been observed.[1,3] Models propose that a necessary condition for positive exchange bias is an antiferromagnetic coupling at the F/AF interface.[3–5] So far, there is no experimental proof for this antiferromagnetic coupling since its direct observation is difficult. However, recent progress in high resolution magnetic imaging with polarized soft x rays allows element specific observation of the spin structure of exchange bias systems.[6,7] To this end, x-ray magnetic circular dichroism (XMCD) which is sensitive to ferromagnetic domains is used as well as x-ray magnetic linear dichroism (XMLD) which enables imaging of antiferromagnetic domains. Ohldag *et al.*[7] studied Co/NiO by x-ray photoemission electron microscopy (PEEM) and found a ferromagnetic coupling between Co and Ni spins at the interface. We investigate the metallic system CoFeB/MnIr which is well suited for devices due to its large value of H_{eb}, its high Néel (690 K)[8] and blocking temperature (400–520 K),[1] low critical thickness, good corrosion resistance, and the soft magnetic behavior of the ferromagnet. We could directly image the domain structure of both the ferromagnet and the uncompensated Mn spins and found an antiferromagnetic coupling at the F/AF interface.

A $Co_{86}Fe_{10}B_4(3\,nm)/Mn_{77}Ir_{23}(10\,nm)/Ni_{80}Fe_{20}(10\,nm)/Si_3N_4(10\,nm)$ exchange biased film was prepared on Si (100) by rf-magnetron sputtering. The NiFe and SiN layers serve as a buffer for the MnIr, which was shown by x-ray diffractometry to have a (111) texture. A dc magnetic field of 8 kA/m was applied during the deposition to generate exchange bias. Its value was enhanced by postannealing in vacuum at 250 °C in a magnetic field of 68 kA/m. The system was micro-patterned using a 22 keV Ga^+ focused ion beam ($\varnothing < 50$ nm), whose etching depth of about 8 nm was monitored by secondary ion mass spectroscopy. Figure 1 shows the magnetization curve of the postannealed system, measured with an alternating gradient magnetometer by applying a magnetic field parallel to the exchange bias direction. The larger and smaller steps of the magnetization are due to the switching of NiFe and CoFeB layers, respectively. CoFeB/MnIr shows a large H_{eb} of 36 kA/m, corresponding

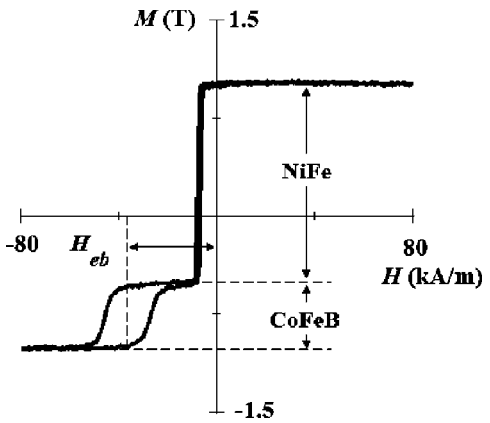

FIG. 1. Hysteresis loop measured with an alternating gradient magnetometer, applying a field parallel to the exchange bias direction.

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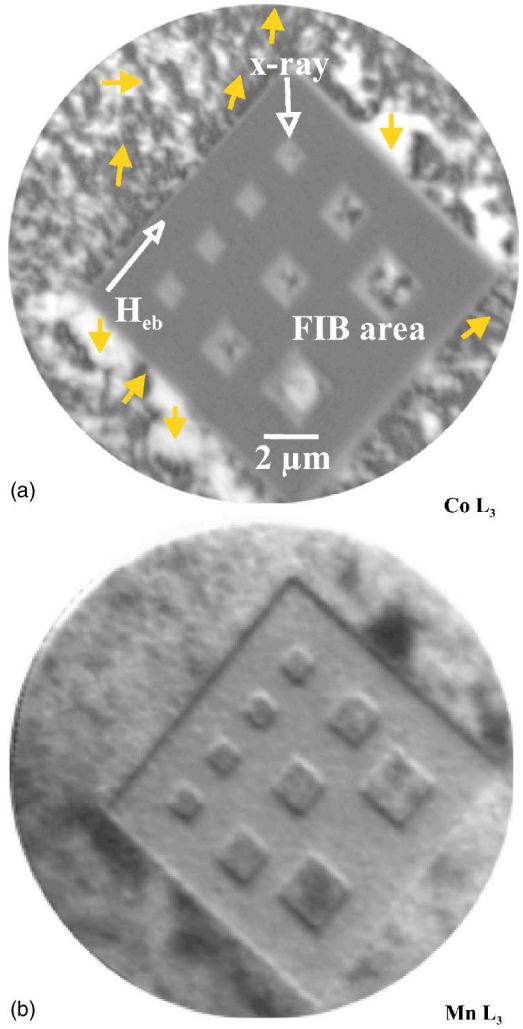

FIG. 2. (Color online) Patterned area of the CoFeB/MnIr/NiFe system taken with PEEM at the (a) Co and (b) Mn L_3 edges. Arrows in some domains of (a) represent their magnetization direction as deduced from the XMCD contrast.

to an exchange energy of $J=0.122$ mJ/m^2. The rather large coercivity H_c of 9.6 kA/m may be caused by the small thickness of the CoFeB layer, set to 3 nm to enable studying the F/AF interface with the surface sensitive PEEM.

We used the photoemission electron microscope at the Surface/Interface Microscopy beamline of the Swiss Light Source (SLS) for magnetic imaging. Figure 2(a) shows a square region of the sample where material was removed by FIB etching, except for quadratic dots with edges of 1, 1.5, and 2 µm length. In the remaining part irregular shaped in-plane domains of several hundred nanometers in width are visible. Since this image was taken at the Co L_3 edge with the element-selective XMCD only the Co moments are probed. Further, inherent to XMCD, the brightness of the domains scales with the projection of their magnetization to the photon propagation direction. Using this relation and assuming the brightest domain has its magnetization parallel to the x-ray direction, the magnetization of the domains pictured by arrows in Fig. 2(a) has been calculated. As a result, the magnetization in most domains points along the exchange bias direction with a spread of orientations relative to this direction of less than 45°. The irregular domain structure and the distribution of magnetization directions in CoFeB is thought to be a result of the random distribution of the anisotropy axis in the AF caused by a measured random orientation of MnIr polycrystals in the (111) film plane. Domains with a higher deviation from the easy direction, visible by a large XMCD contrast [white in Fig. 2(a)], appear only around those edges of the structured area which are perpendicular to the exchange bias direction as well as inside the dots. We attribute this both to local stray fields and to a reduction of H_{eb} due to an increased interfacial mixing caused by the FIB structuring process.[9,10] The same domain structure observed for Co in Fig. 2(a) was also observed at the Fe L_3 edge (not shown), thus proving parallel coupling of Co and Fe spins.

For the disordered γ-phase fcc alloy $Mn_{77}Ir_{23}$ a vanishing XMCD is expected since its magnetic Mn moments are compensated in the (111) film plane, forming a noncollinear, so-called 3Q spin density wave (SDW) structure.[8] XMLD contrast, used to image domains in oxidic antiferromagnets,[6,7] also vanishes for the 3Q SDW structure due to the threefold symmetry in the (111) plane,[11] thus there is no possibility to study AF domains. Yet at the CoFeB/IrMn interface the adjacent FM may induce uncompensated moments in the AF. The high sensitivity of XMCD which we enhanced by dividing images taken with left and right circularly polarized light allows probing such uncompensated spins even if their effective thickness is below a monolayer. Indeed, we found XMCD contrast by tuning the photon energy to the Mn L_3 edge, as shown in Fig. 2(b). Within the experimental accuracy the same domain structure is found as in CoFeB, but with a reversed contrast, indicating an antiparallel alignment between the uncompensated Mn and the ferromagnetic CoFeB spins. This antiferromagnetic coupling might be related to the presence of Fe, as measurements of Mn on Fe(100)[12] and calculations[13] show antiparallel coupling between Fe and Mn. In contrast, a monolayer of Mn on top of Co has been found in a high-spin state with ferromagnetic alignment,[14] which may explain the parallel coupling reported in a similar exchange bias system without Fe, namely in Co(2 nm)/$Mn_{80}Ir_{20}$(20 nm).[15]

To prove the nature of the observed Mn contrast, we did spectromicroscopy by scanning the photon energy at the Mn L edges. From the set of images local x-ray absorption (XAS) and XMCD spectra have been calculated. The XAS spectra of Fig. 3 are taken in two different domains within a dot (see the inset). The multiplet structure of the XAS is similar to calculations[16] of the $3d^5$ configuration of Mn^{2+} in an octahedral symmetry (dashed line in Fig. 3). The XMCD spectrum shown in Fig. 3, obtained by subtracting the XAS spectra of areas 1 and 2 is an unambiguous proof of the ferromagnetic nature of the detected contrast, which we attribute to uncompensated Mn spins at the CoFeB/MnIr interface. According to a measurement in a Co/$Mn_{80}Ir_{20}$ system[15] a fraction of about 5%–10% of this uncompensated moments is expected to be anchored in the AF, i.e., the spins do not follow the external magnetic field and are therefore assumed to be the origin of exchange bias. Thus, investigation of uncompensated interfacial spins and their domain configuration, coupling and temperature behavior, demonstrated to be possible for the technologically important CoFeB/MnIr system, can help to obtain a deeper understanding of exchange bias and to build improved systems. As an example, the observed antiferromagnetic interface coupling may enable positive exchange bias or positive magnetoresistance in CoFeB/MnIr, allowing the construction of bipolar magnetic field

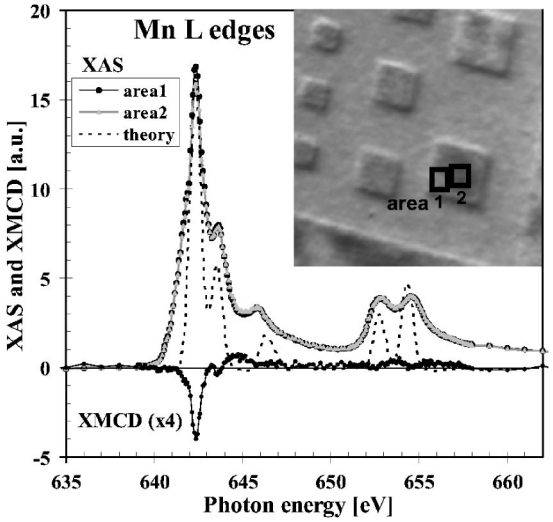

FIG. 3. Mn $L_{2,3}$ XAS and XMCD spectra taken with right circularly polarized light from the areas 1 and 2 indicated in the inset. The XAS is compared to atomic calculation (dashed line) on high spin Mn d^5, $S=5/2$, taken from Ref. 15.

sensors with a higher sensitivity and a linear response.[17]

In summary, the domain structure of a microstructured CoFeB/MnIr exchange bias film has been imaged element-specifically by PEEM and XMCD. Domains inside the dots show higher deviation from the exchange bias direction than domains in unpatterned regions, which we ascribe both to local stray fields and to a reduction of H_{eb} by FIB milling. We could image uncompensated Mn spins and found an antiparallel coupling at the CoFeB/MnIr interface which may enable positive exchange bias in this technologically promising system.

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[1] J. Nogués, and I. K. Schuller, J. Magn. Magn. Mater. **200**, 203 (1999).
[2] H. Ohldag, A. Scholl, F. Nolting, E. Arenholz, S. Maat, A. T. Young, M. Carey, and J. Stöhr, Phys. Rev. Lett. **91**, 017203 (2003).
[3] J. Nogués, D. Lederman, T. J. Moran, and I. K. Schuller, Phys. Rev. Lett. **76**, 4624 (1996).
[4] N. C. Koon, Phys. Rev. Lett. **78**, 4865 (1997).
[5] J. Nogués, C. Leighton, and I. K. Schuller, Phys. Rev. B **61**, 1315 (2000).
[6] F. Nolting, A. Scholl, J. Stöhr, J. W. Seo, J. Fompeyrine, H. Siegwart, J, -P, Locquet, S. Anders, J. Lüning, E. E. Fullerton, M. F. Toney, M. R. Scheinfein, and H. A. Padmore, Nature (London) **405**, 767 (2000).
[7] H. Ohldag, A. Scholl, F. Nolting, S. Anders, F. U. Hillebrecht, and J. Stöhr, Phys. Rev. Lett. **86**, 2878 (2001).
[8] A. Sakuma, K. Fukamichi, K. Sasao, and R. Y. Umetsu, Phys. Rev. B **67**, 024420 (2003).
[9] T. Mewes, R. Lopusnik, J. Fassbender, B. Hillebrands, M. Jung, D. Engel, A. Ehresmann, and H. Schmoranzer, Appl. Phys. Lett. **76**, 1057 (2000).
[10] A. Mougin, T. Mewes, M. Jung, D. Engel, A. Ehresmann, H. Schmoranzer, J. Fassbender, and B. Hillebrands, Phys. Rev. B **63**, 060409(R) (2001).
[11] XMLD shows a $(3\cos^2\theta-1)$ dependence, where θ is the angle between the electric field vector of the linearly polarized light and the magnetic axis. For magnetic axes with a threefold symmetry the sum $\cos^2\theta+\cos^2(\theta+120°)+\cos^2(\theta+240°)$ does not change with θ, i.e., there is no XMLD contrast. Our measurements confirm a vanishing XMLD contrast and thus support the existence of the predicted $3Q$ spin density wave structure.
[12] O. Rader, W. Gudat, D. Schmitz, C. Carbone, and W. Eberhardt, Phys. Rev. B **56**, 5053 (1997).
[13] S. Bouarab, H. Nait-Laziz, M. A. Khan, C. Demangeat, H. Dreyssé, and M. Benakki, Phys. Rev. B **52**, 10127 (1995).
[14] W. L. O'Brien and B. P. Tonner, Phys. Rev. B **50**, 2963 (1994).
[15] H. Ohldag, A. Scholl, F. Nolting, E. Arenholz, S. Maat, A. T. Young, M. Carey, and J. Stöhr, Phys. Rev. Lett. **91**, 017203 (2003).
[16] G. van der Laan and B. T. Thole, Phys. Rev. B **43**, 13401 (1991).
[17] C. H. Marrows, F. E. Stanley, and B. J. Hickey, Appl. Phys. Lett. **75**, 3847 (1999).