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Layer-resolved magnetic imaging of spin-reorientation transitions in Ni/Cu/Co trilayers

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Abstract

Photoelectron emission microscopy (PEEM) in combination with magnetic circular dichroism in soft X-ray absorption (XMCD) allows the layer-resolved microscopic imaging of magnetic domains. This is applied for the study of ultrathin epitaxial Co/Cu/Ni/Cu(0 0 1) trilayers. At about 1.9 atomic monolayers (ML) Co on 4 ML Cu/15 ML Ni a spin-reorientation transition of the Co layer between out-of-plane and in-plane, accompanied by a transition from collinear to non-collinear alignment between Co and Ni is observed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic coupling—interlayer; Spin reorientation transitions; X-ray dichroism; Anisotropy—thin films

Ferromagnet/non-ferromagnet/ferromagnet (FM/NM/FM) trilayer structures are at the heart of any application taking advantage of giant magnetoresistive effects. Because of the shrinking lateral size of typically employed elements, microscopic imaging techniques are desirable for the study of such trilayers. Photoelectron emission microscopy (PEEM) with magnetic circular dichroism in soft X-ray absorption (XMCD) as contrast mechanism is one such technique that has already proven its versatility for the imaging of magnetic domains in ultrathin films [1–3]. A rather important point for the study of layered structures is the element-specificity of XMCD–PEEM, which is achieved by tuning the exciting X-ray radiation to the different elemental core level absorption edges. Since also buried layers can be studied, it thus allows the layer-resolved domain imaging of magnetic trilayers, provided that different elements are used in the different magnetic layers.

In this contribution we use XMCD–PEEM to study the domain images and the magnetic coupling in trilayers containing magnetic layers with competing anisotropies. If in a trilayer of the type FM1/NM/FM2 the magnetic layer FM1 has an easy axis of magnetization in the film plane ("in-plane"), and FM2 an easy axis of magnetization perpendicular to the film plane ("out-of-plane"), these two single layer anisotropies compete by the interlayer coupling. The two limiting cases of very strong and very weak coupling are intuitively clear: for very strong coupling the magnetization directions of the two layers will be forced to be collinear, whereas in the limit of vanishing coupling the individual easy directions of magnetization will be assumed, leading to a non-collinear configuration. For intermediate coupling more complicated configurations of non-collinear magnetizations and spin-reorientation transitions can occur.

In the present study we use Co as FM1, Cu as NM, and Ni as FM2. This trilayer is grown epitaxially on Cu(0 0 1) at room temperature. Whereas Co films on Cu(0 0 1) are always magnetized in the film plane [4,5], Ni films show a perpendicular magnetization in an extended thickness range [6–8]. From layer-resolved PEEM domain images of the as-grown trilayer, acquired at the Ni and Co L_3 edges, we can directly identify regions of collinear and non-collinear alignment, and study the spin-reorientation transitions in between.

The Ni, Cu, and Co layers were evaporated by electron bombardment of high purity rods with typical deposition rates of 0.5 atomic layers (ML) per minute.

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After deposition of 15 ML Ni and 4 ML Cu, the top Co layer is deposited as a 320 μm wide wedge of 0–6 ML by placing an aperture of $2 \times 0.5\,\text{mm}^2$ in front of the sample, and rocking the sample-mask assembly about the long axis of the aperture during film deposition, as described in more detail in Ref. [9].

The setup of the photoemission microscope (Focus IS-PEEM) is identical to that described in previous publications [3]. Parameters were set to result in a lateral resolution of 0.4 μm and a field of view of 60 μm. Images are presented in the form of grayscale coded absorption asymmetry for opposite light helicity at the maxima of the Ni and Co L_3 edges, respectively. The asymmetry is proportional to the cosine of the angle between the local magnetization direction and the light incidence.

The measurements were performed at the helical undulator beamline UE56-2 PGM2 of BESSY II in Berlin. Circularly polarized light with a degree of polarization of about 80% was used, incident to the sample under an angle of 60° from the surface normal.

Fig. 1 shows domain images of the Co/Cu/Ni trilayer. Panels (a) and (c) on the left-hand side show the domain pattern of the Ni layer, panels (b) and (d) on the right-hand side the domain pattern of the Co layer. The Co thickness increases in the images from ≈1.3 ML at the top to ≈2.4 ML at the bottom, as indicated at the axes at the left-hand side. In the top and bottom images approximately the same area of the sample is imaged for different azimuth angles of light incidence, as indicated in the figure by arrows labeled "*hv*". From these two measurement geometries the two angles of the magnetization vector in space can be determined. Since the relative orientation of out-of-plane magnetization direction and light incidence does not change for rotation of the light incidence about the sample normal, no change in contrast is expected for out-of-plane domains. For in-plane domains, on the contrary, the relative orientation between the magnetization direction and the light incidence direction changes as the azimuth of the exciting X-rays is rotated. For in-plane magnetized domains a contrast reversal is consequently expected for a ≈180° rotation of the incidence azimuth.

Comparing the Co images (b) and (d), two regions with different behavior upon light incidence variation are clearly distinguished: Whereas the (weaker) contrast in the top part of the image remains unchanged, the contrast in the bottom part reverses. We can thus conclude that out-of-plane magnetization is present in

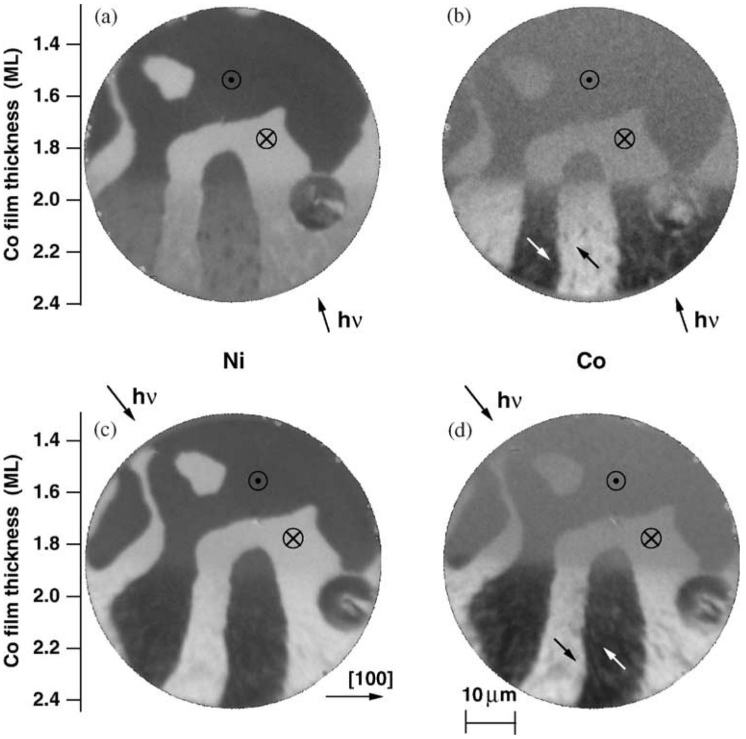

Fig. 1. Layer-resolved magnetic domain images of an epitaxial Co/4 ML Cu/15 ML Ni trilayer on Cu(0 0 1). The Co thickness increases from top to bottom, as indicated at the left-hand side. (a) and (c) show the domain pattern of the Ni layer, (b) and (d) the domain pattern of the Co layer. The light incidence was from the lower right for (a) and (b), and from the upper left for (c) and (d), as indicated. A region of collinear out-of-plane magnetization is observed in the top part of the image; in the bottom part a non-collinear configuration of in-plane Co and canted Ni magnetization is observed.

the top part of the image, and in-plane magnetization along the $[1\,\bar{1}\,0]$ and $[\bar{1}\,1\,0]$ directions in the bottom part, as indicated by arrows. In between these two parts a spin-reorientation transition takes place in the Co layer. The circular feature in the images is a macroscopic defect in the substrate, which helped to quickly relocate the same spot on the sample after azimuth rotation.

In the Ni domain images (a) and (c) no contrast reversal as in the bottom part of the Co images is observed. However, also here the top and bottom parts of the images behave differently under azimuth rotation. Like in the Co images, the contrast in the top part of images (a) and (c) is identical. Also the Ni magnetization is out-of-plane in that part of the image, and Ni and Co magnetization directions are collinear. Even though the contrast in the bottom part of the Ni images does not reverse, there is a substantial difference between image (a) and (c): the contrast between bright and dark domains is stronger in (c) than in (a). We can conclude that here neither a pure out-of-plane orientation nor a pure in-plane orientation is present. Quantitative analysis of the grayscale contrast reveals that here the Ni magnetization is canted by about 23° away from the out-of-plane direction into the $[1\,\bar{1}\,0]$ and $[\bar{1}\,1\,0]$ in-plane directions of the corresponding Co domains.

The spin-reorientation transition in the Co layer and the corresponding transition between collinear and non-collinear alignment between the Co and Ni magnetizations can be understood from the competition between the Ni and Co uniaxial anisotropies and the interlayer coupling across the Cu spacer layer. For very low Co thicknesses in the top of the images, the Curie temperature T_C of the Co layer is close to room temperature, which is manifest in the weak contrast at that position. Both the magnetostatic and magnetocrystalline contributions to the Co anisotropy are strongly reduced close to T_C. The Co layer is thus easily rotated to assume a collinear out-of-plane magnetization with the Ni layer. For higher Co thicknesses the Co in-plane anisotropy is rapidly increasing significantly beyond the absolute value of the Ni anisotropy, leading to a canting of the Ni magnetization at the intermediate interlayer coupling strength present at 4 ML Cu [10].

In conclusion, layer-resolved magnetic imaging by XMCD–PEEM revealed a spin-reorientation transition in a coupled Co/Cu/Ni trilayer between a collinear out-of-plane configuration for low Co thicknesses and a non-collinear configuration for higher Co thicknesses. In the latter the Co magnetization is in-plane, whereas the Ni magnetization is canted at an oblique angle between out-of-plane and in-plane. This spin-reorientation transition is driven by the variation of the Co uniaxial anisotropy as a function of Co layer thickness.

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