# Layer-resolved imaging of non-collinear magnetization in Ni/Cu/Co trilayers

*W. Kuch, Xingyu Gao and J. Kirschner*

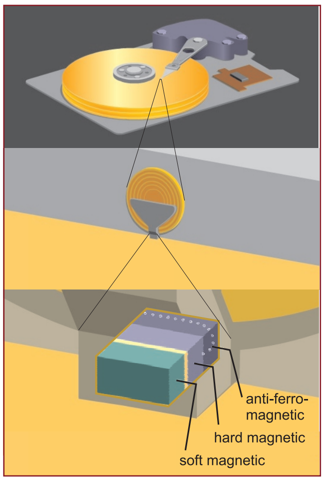


***Fig. 1:* Structure of a magnetoresistive write/read head for computer hard disks. The actual head is sitting on the front of the glider. Functional elements are two magnetic layers.**

Fundamental research and industrial development in the field of thin film magnetism have soared dramatically during the last decade. This is to a large extent due to the discovery in the late eighties of giant resistivity changes in magnetic trilayers, in which two magnetic layers are separated by a non-magnetic spacer layer [1, 2]. Less than ten years after this discovery, the first commercial applications of the effect were on the market. Fig. 1 shows as an example a computer hard disk read head, as it is delivered nowadays in millions of laptop and desktop computers. Because of the high fundamental interest and the technological importance, the magnetic coupling between two ultrathin magnetic layers, separated by a non-magnetic spacer layer as in the bottom panel of Fig. 1, is a field of intense research. In such trilayers the competition between different energy contributions of magnetically coupled systems can lead to non-collinear and canted magnetic configurations [3].

The study of such phenomena and systems requires a method that allows access to the microscopic magnetic domain pattern of each of the magnetic layers separately. Photoelectron emission microscopy (PEEM) using X-ray magnetic circular dichroism (XMCD) in soft X-ray absorption as a contrast mechanism is such a technique [4]. In this method, the local intensity of emitted low-energy secondary electrons for resonant excitation of elemental X-ray absorption edges is imaged by a set of electrostatic lenses.

The local secondary electron intensity is a measure for the local X-ray absorption, which depends on the relative orientation of the magnetization direction and the direction of the incoming, circularly polarized X-rays. The element-sensitivity of XMCD can be used to obtain layer-selective magnetic domain images if the different layers contain different elements. XMCD-PEEM is therefore ideally suited to study non-collinear magnetic configurations in coupled magnetic systems.

We present here a layer-resolved XMCD-PEEM study of the magnetic domain patterns of Co/Cu/Ni trilayers, epitaxially grown on Cu(001). Ni and Co films on Cu(001) are known to exhibit different magnetic properties: Whereas Co films are always magnetized in the film plane [5], Ni films show a perpendicular magnetization in an extended thickness range [6]. Definite conclusions about canted and non-collinear magnetization configurations can be drawn, independent of domain formation, from comparing magnetic domain patterns of the Ni and Co layers at the same sample position. We show that for appropriate layer thicknesses reorientation transitions between collinear and non-collinear configurations occur, in the course of which the Ni layer assumes a canted magnetization.

The measurements were performed at the helical undulator beamline UE56-2 (Max-Planck-CRG). Circularly polarized light of the fifth harmonic with a degree of polarization of about 80% was incident to the sample under an angle of 60° from the surface normal. A commercial electrostatic PEEM was used (Focus IS-PEEM). Parameters were set to result in a lateral resolution of 400 nm and a field of view of 60 $\mu$m. Ni was deposited as a continuous layer on the clean Cu(001) single crystal. Co and Cu layers were shaped into 320 $\mu$m wide crossed wedges with a 180 $\mu$m wide plateau of constant thickness at the upper end of the wedge.

Fig. 2 shows domain images of a Co/Cu/Ni trilayer at low Co thicknesses and a constant Cu thickness of 4 atomic monolayers (ML). The Co thickness increases from bottom to top, as indicated at the left axis. Panels (a) and (c) on the left hand side show the domain pattern of the Co layer, panels (b) and (d) on the right hand side the domain pattern of the Ni layer. The top and bottom images show approximately the same position of the sample for different azimuth angles of the light incidence, as indicated by the arrows labeled 'h$\nu$'.

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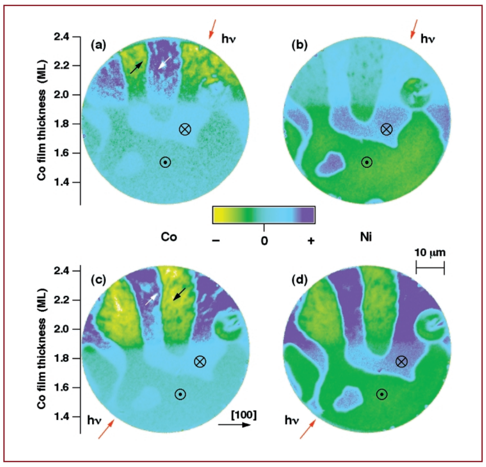



***Fig. 2:***
***Layer-resolved domain images of a wedged Co/4 ML Cu/15 ML Ni trilayer on Cu(001). The Co thickness increases from bottom to top. (a), (c): Co layer. (b), (d): Ni layer. (a), (b) and (c), (d) are images obtained for different light incidence angles, as indicated by arrows labeled 'hν'. In the lower part of the imaged area Co and Ni magnetizations are collinearly aligned out-of-plane, in the upper part the Ni magnetization is at a canted non-collinear direction***

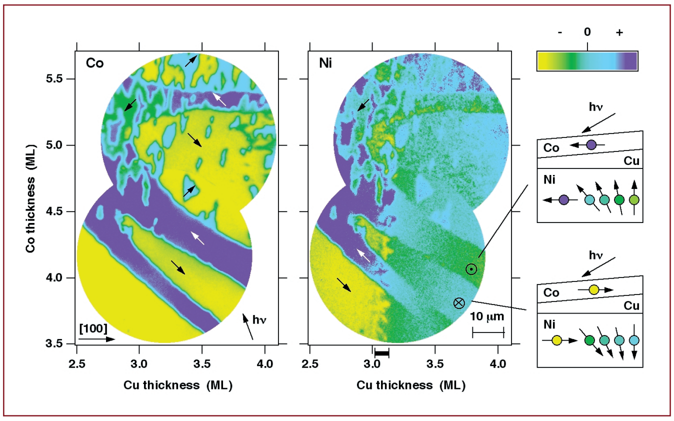
The images are a color-coded representation of the projection of the local magnetization direction onto the light incidence direction, as indicated by the legend in the center of the image. The two angles of the magnetization vector in space can be determined from these two measurement geometries. In particular, for pure out-of-plane magnetization no change in contrast is expected upon changing the incidence azimuth. For in-plane magnetization, on the contrary, a contrast reversal occurs for reversing the X-ray incidence direction.

Comparing the images of Fig. 2 it is seen that in the lower part of the images the Co and Ni magnetizations are aligned in a collinear out-of-plane configuration. In the upper part, the Co layer exhibits an in-plane magnetization, as evidenced from the reversing contrast between panels (a) and (c). In this region the Ni does exhibit a change in contrast, but not a reversal as expected for in-plane magnetization. Here consequently the Ni magnetization is neither purely out-of-plane nor fully in-plane, but something in between. In the upper part of the images a non-collinear magnetization configuration is present, in which the Co layer is magnetized in-plane, whereas the Ni layer is magnetized along canted axes [7]. For the very low Co thicknesses present in Fig. 2, the Curie temperature of the Co layer is close to room temperature. The magnetic anisotropies are strongly reduced close to the Curie temperature, so that the magnetization of the Co layer is here easily rotated out-of-plane by the interlayer coupling.

Fig. 3 shows color-coded domain images for a Co layer and a Ni layer of a crossed Co/Cu double wedge on 15 ML Ni/Cu(001).

As in Fig 2, reorientation transitions between collinear and non-collinear configurations of the Co/Cu/Ni trilayers have been observed, but while the collinear configuration was out-of-plane in Fig. 2, it is in-plane in Fig. 3. In both cases the Ni was magnetized along a canted direction in the non-collinear configuration. This canting can be understood considering the competition between the magnetic anisotropies of the Co and Ni layers and the magnetic interlayer coupling across the Cu spacer layer. Whereas the perpendicular anisotropy of the Ni layer tends to orient Ni out-of-plane, the interlayer coupling tries to align it parallel with the Co moment, thus leading to a canted configuration [8].

***Fig. 3:***
***Layer-resolved domain images (left: Co, right: Ni) of a crossed Co/Cu double wedge on 15 ML Ni/Cu(001). The Cu thickness increases from left to right, the Co thickness from bottom to top. In the leftmost part of the images Ni and Co magnetizations are in-plane and collinear. In the right part of the images, the Ni magnetization exhibits a gradual canting as a function of Cu spacer layer thickness, leading to a non-collinear configuration. The gradually changing magnetic contrast is schematically explained at the right hand side.***




**Contact:**
Wolfgang Kuch,
Max-Planck-Institut für Mikrostrukturphysik, Halle
*kuch@bessy.de*