## MAGNETIC DOMAIN IMAGING WITH A PHOTOEMISSION MICROSCOPE

The rapidly decreasing size of a bit of magnetically stored information calls for techniques that allow the laterally resolved study of magnetic samples on a sub-micron scale. Photoelectron emission microscopy (PEEM) is one such technique. It can provide element-resolved surface-sensitive images of the magnetization component along the direction of the incoming photon beam when magnetic circular dichroism (MCD) in soft X-ray absorption is used as a magnetic contrast mechanism. Using this technique, the intensity of the emitted secondary electrons at the absorption maximum of elemental absorption edges is imaged. This intensity is dependent upon the relative orientation of magnetization direction and light helicity vector [1].

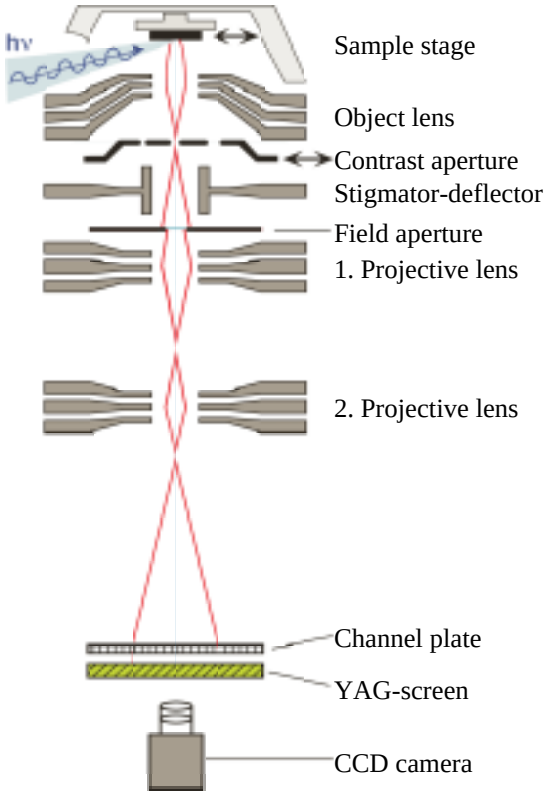


*Fig. 1. Principle of the photoelectron emission microscope.*

We have obtained domain images of the spin reorientation transition in ultrathin epitaxial Co/Ni bilayers using a photoemission microscope at the soft X-ray twin helical undulator beamline **BL25SU**. These measurements are the result of a collaboration between the Max-Planck-Institut für Mikrostrukturphysik in Halle, Germany, the Department of Material Physics of Osaka University and SPring-8. A sketch of the PEEM is shown in Fig. 1. The sample is illuminated by circularly polarized X-rays, and a magnified image of the emitted low-energy secondary electrons is obtained by a set of electrostatic lenses. This image is optically recorded from a fluorescent screen using a CCD camera.

For commercial applications of ultrathin magnetic films it is important to control the preferred axis of magnetization. This axis is determined by the free energy minimum, the magnetization-direction-dependent component of which is called anisotropy energy. This energy is dependent upon the magnetostatic demagnetizing energy, and the electronic structure via spin-orbit coupling. In ultrathin films the latter is strongly influenced by strain, symmetry breaking, reduced coordination number and hybridization at the interfaces and at the surface. As a result, in Ni films on Cu(001) the magnetization is perpendicular to the plane of the film ("out-of-plane") in an extended thickness region [2], whereas in Co films on Cu(001) it is always in the film plane ("in-plane") [3]. Stacking both films on top of each other should thus constitute a means of effectively setting the anisotropy energy at a desired value, and controlling the magnetic easy axis.

We have studied the spin-reorientation transition in Co/Ni/Cu(001) crossed double wedges. The films are schematically shown in the top of Fig. 2. First, a wedge-shaped film of 0-14 ML Ni was deposited onto the Cu(001) substrate with thickness increasing from left to right, and then capped by a wedge-shaped Co layer of 0-4 ML with thickness increasing from bottom to top. In this way, any combination of Ni and Co thicknesses

within those ranges can be attained at a particular position in the sample. A magnetic domain image of a $55 \times 97$ μm$^2$ region of the sample is presented at the bottom of Fig. 2. The Ni and Co thicknesses at that position are given by the upper and right axes, respectively.

Contrast is obtained from the intensity asymmetry of two images acquired at the Ni $L_2$ and $L_3$ edges, and represented in a color scale where red and blue represent opposite signs of asymmetry, while white corresponds to zero. Assuming a constant moment in the Ni film, these colors can be

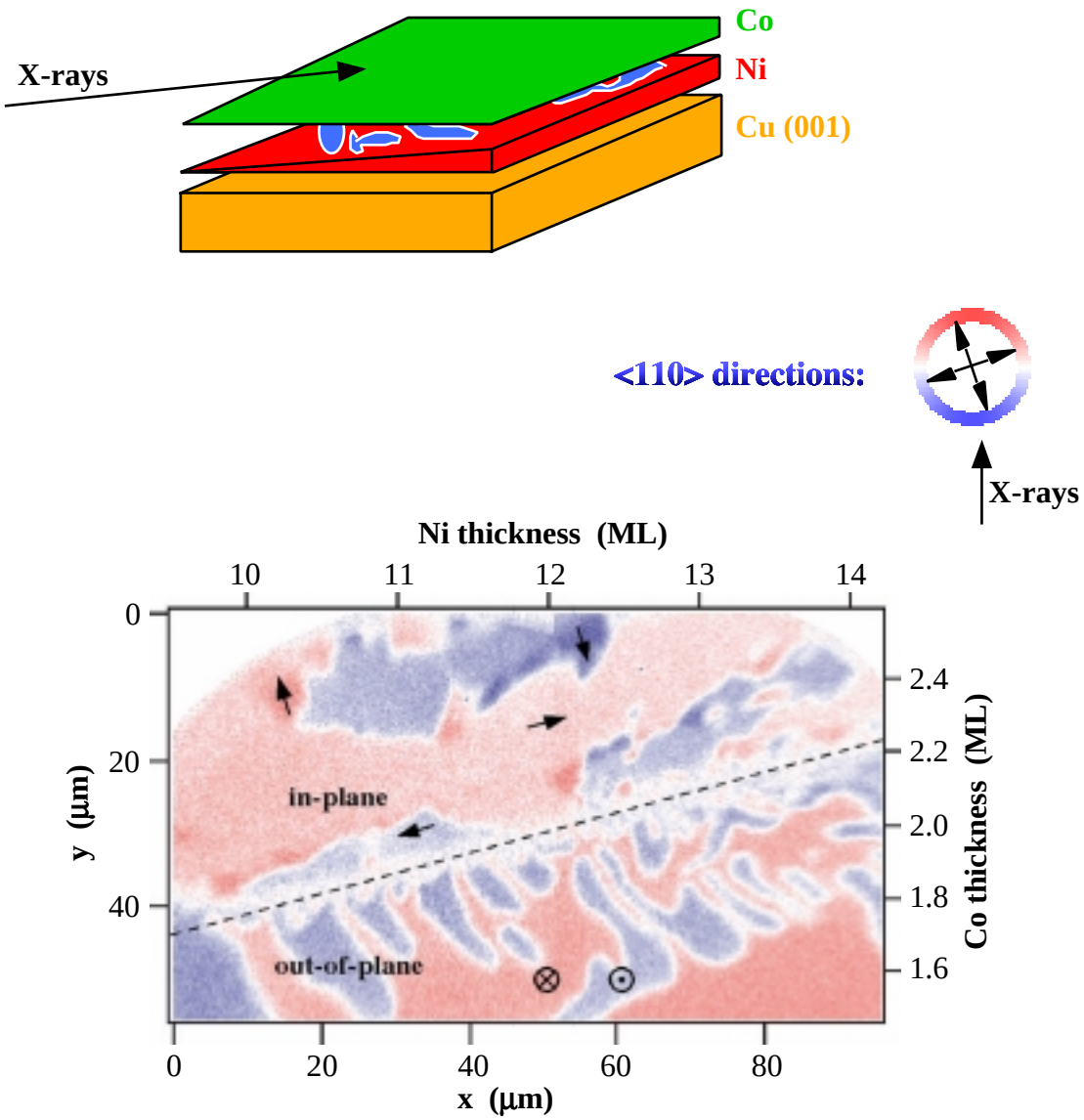


*Fig. 2.* ***Top****: Schematics of the Co/Ni crossed double wedge on Cu(001).* ***Bottom****: Microscopic domain image at the spin reorientation transition. Red and blue colors correspond to opposite orientations of the magnetization direction; the intensity of the coloring represents the magnitude of the component along the light incidence direction, as indicated in the text. Arrows in the image mark the magnetization directions of selected domains. In the lower part of the image out-of-plane magnetization is favored, while in the upper part in-plane magnetization along the four equivalent <110> crystallographic directions is formed.*

correlated to the projection of the magnetization direction onto the incoming X-ray beam, which in the present case was at an angle of 30° above the image plane, approaching from the bottom of the image. An analysis of the different asymmetry levels leads to the following interpretation: In the region below the dotted line, the two different asymmetry levels, blue and red, correspond to perpendicularly up and down magnetized domains, respectively, as indicated in the figure. Above the dotted line, four different color levels (dark blue, light blue, light red and dark red) are observed, which correspond to magnetization directions along the four equivalent <110> in-plane crystallographic directions. The correlation of color representation to the in-plane angle of magnetization is explained by the small circle in Fig. 2.

A spin reorientation transition takes place at the dotted line. The magnetization switches from in-plane to out-of-plane for increasing Ni thickness and/or decreasing Co thickness. It is seen that the average domain size shrinks as this line is approached from the out-of-plane side. This can be explained by the competition between the magnetostatic energy on the one hand, and the energy cost for creating domain walls on the other hand. Closely spaced alternating up and down magnetized perpendicular domains have a lower magnetostatic energy than a single out-of-plane domain due to partial flux closure. The formation of such domains can be energetically favorable close to the spin-reorientation transition because at that point the anisotropy energy and hence the energy for the formation of domain walls (in which an in-plane component of the magnetization appears) is low.

The ability to extract full MCD spectroscopic information on a microscopic scale from photon energy scans of such images (microspectroscopy) allows us to address the connection between the anisotropy of the orbital magnetic moment and the magnetic anisotropy energy in these films [4]. This demonstrates the enormous potential of the present technique.

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**References**

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