Magnetic phase transition in Fe monolayers on Ni/Cu(100) observed by SPLEEM and XMCD


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Ferromagnetic bilayer systems consisting of two metals that show opposite spin reorientation transitions (SRT) as a function of temperature and thickness are of fundamental interest. Fe/Cu(100) shows a reorientation of the magnetization from out-of-plane at low thickness and temperature to in-plane at larger thickness and temperature around 10 monolayers (ML) at 300 K.1 Ni/Cu(100) is known to exhibit a continuous anomalous SRT. At low thickness and temperature the easy axis of the magnetization lies in the film plane, at larger thickness and temperature the magnetization turns out of the plane. At 300 K the transition occurs between 7 and 10 ML.2,3


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**Notes:**
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We performed in-situ XMCD- and SPLEEM\textsuperscript{4,5} measurements on the reorientation transition of Ni/Cu(100) and the bilayer system Fe/Ni on Cu(100) at beam line D1011 at Maxlab, Sweden, and at the NCEM in Berkeley, USA, respectively.

Fig. 1: XMCD spectra of 8 ML Fe on 11 ML Ni/Cu(100) at 30° grazing incidence. Both Fe and Ni are in-plane magnetized.

Fig. 2: XMCD spectra of 8 ML Fe on 11 ML Ni/Cu(100) at 30° grazing incidence. Both Fe and Ni are in-plane magnetized.

By making use of the element specificity of the XMCD technique we were able to characterize the magnetic behaviour of the Fe and the Ni layers separately, which helped us to better understand the micromagnetic domain structure of the bilayer system imaged by SPLEEM. The main focus was the determination of the magnetization direction in Fe monolayers on top of perpendicularly magnetized Ni/Cu(100) films. X-ray absorption spectra have been recorded at both the Fe and the Ni edges at 300 K. On perpendicularly magnetized Ni of about 11 ML thickness Fe layers of 0.5 ML and 2 ML were evaporated. For both thicknesses the Fe is perpendicularly magnetized. Fig. 1 shows the XMCD spectra of both the Ni and the Fe edges. A coverage of 0.5 ML Fe on Ni shows qualitatively the same results as 2 ML Fe on Ni but the dichroic signal is smaller (not shown here). At about 2.6 ML Fe we found no XMCD at normal incidence. The magnetization of both the Fe and the Ni layers lie in the film plane. The perpendicular remanent magnetization of the Fe is stabilized by the perpendicular magnetization of the Ni underlayers below the SRT of Fe. Above the SRT of Fe which occurred between 2 and 2.6 ML the magnetization of the Ni film was forced into the film plane. A 8 ML thick Fe film on 11 ML Ni was measured after 10 hours at a base pressure below 10\textsuperscript{−8} Pa, resulting in a coverage of about 1 ML CO and CO\textsubscript{2}. The XMCD signal of this bilayer is shown in Fig. 2. Both the Fe and the Ni layers reveal an in-plane magnetization. Interestingly, the XMCD signal of


Fig. 3: SRT of the Fe/11 ML Ni/Cu(100) bilayer system. At 1 ML Fe a canted spin structure exists with mainly out-of-plane direction and an in-plane orientation around 110°. With increasing Fe layer thickness the SRT from out-of-plane to in-plane takes place between 2.5 and 2.9 ML Fe by domain wall proliferation and continuous spin rotation. The easy direction of the in-plane component changes from around 122° (302°) at 1 ML to around 32° (212°) at 2.9 ML Fe after the SRT within the white (black) domains.

the 8 ML Fe (Fig. 2) is much weaker than the signal from the 2 ML film (Fig. 1). This may be due to the adsorption of CO and CO₂. One could tentatively assign the reduction also to the fact that in the 8 ML thickness regime the Fe has just one live top layer which is ferromagnetic, capping antiferromagnetically coupled underlayers⁶, in the 2 ML Fe film both layers are ferromagnetic.

The XMCD signal of the Ni film covered with 8 ML Fe (Fig. 2) is smaller and more noisy than the same Ni film covered with two Fe layers (Fig. 1) due to absorption of the additional Fe cap layers. The XMCD spectra show that in all investigated bilayer systems the Fe and Ni layers couple ferromagnetically to each other, resulting in a common

direction of the magnetic moments in the plane for thick Fe layers and out-of-plane for thin Fe layers. Element specific hysteresis loops (not shown here) confirm the XMCD results of the 8 ML Fe on 11 ML Ni. The loops were recorded at the Fe L₃ edge and the Ni L₃ edge separately at 10° grazing incidence with a diode which yields a signal that is proportional to the magnetization. Both hysteresis loops have nearly the same rectangular shape which means that the magnetic field was applied in the easy direction, namely in the film plane. The same coercive field of 20 Oe for Fe and Ni was found.

Moreover the thickness dependent SRT of Fe monolayers on perpendicularly magnetized Ni (11 ML) on Cu(100) has been studied at 300 K and a base pressure of 2 · 10⁻⁸ Pa by SPLEEM. The Fe film was found to exhibit a strong out-of-plane magnetization up to about 2.4 ML forming large domains of some 10 µm extension. Also a clear in-plane component of the magnetization around 110° is found here indicating a canted spin structure. The SRT from out-of-plane to in-plane takes place between 2.5 and 2.9 ML Fe. Above 2.9 ML Fe the bilayer system is completely in-plane magnetized. Figure 3 demonstrates the domain formation during Fe deposition.

The out-of-plane Fe domains first break up into stripe domains with increasing Fe layer thickness like in Fe/Cu(100) while keeping the spin orientation nearly constant which is indicated by the unchanged MC up to about 2.5 ML. While the stripe domains assemble into large domains again on further Fe deposition the spins reorient continuously into the film plane which is confirmed by the increasing sharpness of the MC in the image series for three different in-plane angles in figure 3. The direction of the in-plane component of the magnetization changes from about 122° (302°) at 1 ML to about 32° (212°) at 2.9 ML Fe after the SRT within the white (black) imaged domains.

In summary SPLEEM measurements unambiguously showed the canted spin structure of Fe/Ni/Cu(100) thin films and the break-up into stripe domains near the SRT. Element specific XMCD experiments demonstrated that the spin orientation in the Fe and Ni layers are parallel throughout the reorientation process.

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