Element-specific magnetization curves and crossover in Co/Cu/Ni/Cu(001) trilayers studied by XMCD

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We present temperature-dependent measurements via the element-specific XMCD technique for Co/Cu/Ni trilayers for cases where the ordering temperature of Co is lower than the one of Ni. Our work focuses mainly on the influence of the interlayer coupling on the shape of the temperature-dependent magnetization curves of Ni. By selecting 1.3 ML of Co and 4 ML of Ni we get a lower T_C(Co)$\approx$ 90 K and a higher T_C(Ni)$\approx$ 180 K. The crossing of the $M(T)$ curves leads to a rotation of the remanent magnetization of Ni. A case where the sublayer magnetizations change gradually their angle as a function of the temperature is recorded and attributed to a competition between coupling and anisotropy mechanisms.

Keywords: Curie temperature, interlayer exchange coupling, temperature-dependent reorientation

1. Introduction

In the last decade many studies on the magnetic properties of multilayers, such as interlayer coupling, giant magnetoresistance and quantum well effect, have been performed. Recently, the influence of interlayer exchange coupling J_{inter} across non-magnetic layers onto the fundamental magnetic observables like the magnetization, magnetic susceptibility and the Curie temperature of the ferromagnetic layers has been investigated (Bovensiepen *et al.*, 1998; Ney *et al.*, 1999; Jensen *et al.*, 1999). As a suitable system to investigate these basic quantities we chose prototype-like Co/Cu/Ni-trilayers on Cu(0 0 1) with well-defined crystalline structure. Taking the advantage of the element-specifity of X-ray magnetic circular dichroism (XMCD), individual temperature-dependent magnetizations $M(T)$ for Co and Ni exhibiting separate ordering temperatures $T^{\star}$(Ni) (the lower one) and T_C(Co) (the one of the trilayer) were probed. Correlation was found between J_{inter} and $T^{\star}$(Ni) as a function of the Cu-spacer thickness and stimulated theoretical work by Jensen *et al.*, 1999 and Wu *et al.*, 2000 on this system.

In our previous works (Bovensiepen *et al.*, 1998; Ney *et al.*, 1999; Jensen *et al.*, 1999) the focal point was the effect of J_{inter} on the magnetic susceptibility and the increase of the lower ordering temperature, that of Ni. Therefore, our measurements were performed near the temperature $T^{\star}$(Ni). Here, on the other hand, we probe the full $M(T)$ of Ni and the $M(T)$ of Co. To enhance our observations, we select a Co thickness of only 1.3-1.4 ML. Thus the ordering temperature of Co is below that of Ni. Then, the ultrathin Co film undergoes a ferro- to paramagnetic transition in the presence of a ferromagnetic Ni film. With our new configuration we reveal interesting cases where J_{inter} induces a spin reorientation or a gradual rotation of $M_{Ni}(T)$ from almost parallel (at low temperatures) to almost antiparallel (at higher temperatures) with respect to $M_{Co}(T)$.

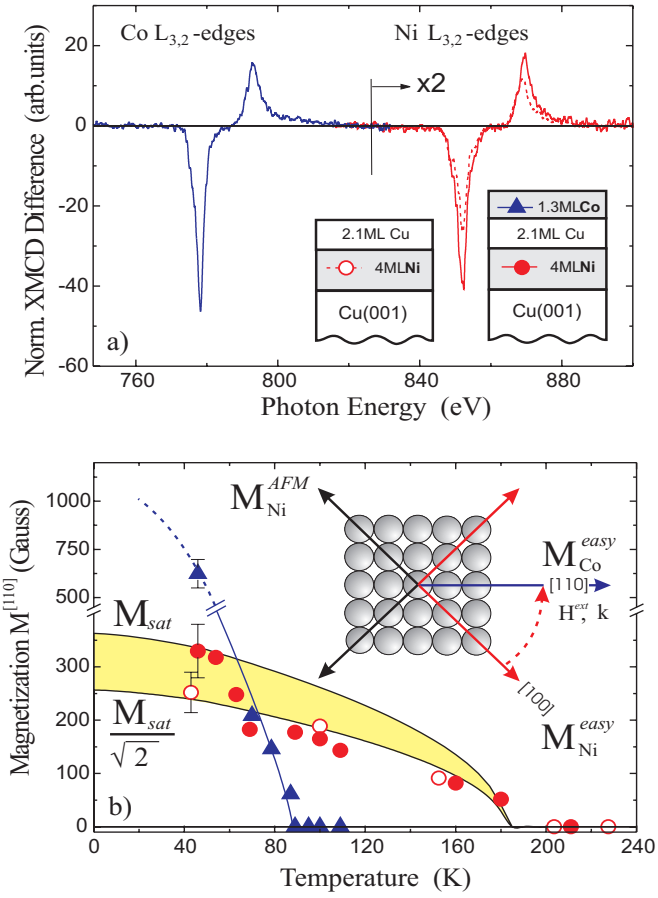

Figure 1
a) XMCD spectra for the bi- and trilayer at 45 K. **b)** Crossing remanent magnetization curves measured along the [110] for Co and Ni as a function of temperature. The lines are guides to the eye. The inset is used for better illustration.

2. Experiment

The Ni, Cu and Co films were grown successively at room temperature (290-305 K) on Cu(0 0 1) under ultrahigh vacuum (UHV) conditions. The Cu single crystal was prepared by several cycles of Ar^+ bombardement and annealing to 900 K. The Ni films of about 4 ML were deposited and softly annealed to 350 K in order to reduce the surface roughness. On the top of Ni a 2-2.5 ML Cu film was grown. The bilayer and the trilayer with the ultrathin 1.3-1.4 ML Co film on top were not annealed to avoid interdiffusion. The thickness calibration, with an accuracy of 0.1 ML, was done by medium energy electron diffraction oscillations and in the case of Cu by a quartz microbalance and then cross checking the Ni, Cu and Co $L_{3,2}$ edge-jump ratios.

The element-specific magnetization curves $M(T)$ were carried out at the SX700 monochromator beamline at the synchrotron facility BESSY I in Berlin. The Ni and Co $L_{3,2}$ absorption edges

were recorded in the partial electron yield (PEY). The XMCD spectra were taken by reversing the remanent magnetization with a pulse driven magnet and keeping the helicity of the incident light fixed. All these trilayers have their easy-magnetization direction in-plane and were measured at 20° grazing incidence of the light. The fixed in-plane geometry was chosen so that the *k*-vector was along [110], which is the easy-magnetization axis for thin Co film on Cu(0 0 1). The degree of circular polarization for that beamline is 71±5 %. The Co and Ni $L_{3,2}$ absorption spectra were normalized to a constant edge jump (0 to 100 arb. units) and corrected for saturation effects. In order to give $M(T)$ in Gauss, we determined the ground state moment for Ni in the bilayer at a reduced temperature $t = T/T_C \approx 0.3$ by applying the sum-rules and extrapolating down to $t = 0$. The $M(T)$, i.e. the normalized XMCD intensities, for Co and Ni were scaled to that ground state moment. The change in the number of *d* holes n_h for Co and Ni, which is thickness-dependent, were taken into account. More details about this analysis, e.g. the applicability of sum-rules and the number of *d* holes for thin films, can be found in Srivastava *et al.*, 1998 and references therein.

3. Results and Discussion

Fig. 1(a) presents the normalized XMCD spectra for the bilayer (dashed line), i.e. 4 ML Ni capped with 2.1 ML Cu, and for the trilayer (solid lines) with ultrathin 1.3 ML Co on top at 45 K. The same sign of the dichroic signal for Co and Ni at the $L_{3,2}$-edges indicates that both are coupled ferromagnetically. The Co signal is roughly 2-3 times larger than the Ni one. Fig. 1(b) shows the element-specific magnetization for Co (solid triangle) and Ni in the bilayer (open circles) and trilayer (solid circles) as a function of temperature. The Curie temperature $T_C(\mathrm{Ni}) = 185 \pm 10$ K of 4 ML Ni in the bilayer is reduced by Cu-capping (Wilhelm *et al.*, 2000). Concerning Ni in the bilayer, we found the same T_C for the trilayer system. This is expected, since the Co magnetization curve vanishes at $T^\star(\mathrm{Co}) = 90\mathrm{K} < T_C$, i.e. no XMCD signal is recordable within the noise for four data points at 90-110 K. It was demonstrated by Ney *et al.*, 1999 that the lower ordering temperature $T^\star$ depends on the strength of interlayer exchange coupling J_{inter} and is always shifted to higher temperatures compared to the uncoupled case in the bilayer. Since the T_C of the single 1.3 ML Co film cannot be measured separately in this experiment, there is no direct investigation of this effect. The T_C for a single Co film on Cu(0 0 1) varies strongly with the thickness in the considered range. However, for 1.3 ML single Co film on Cu(0 0 1) one expects $T_C \approx 80$ K from previous investigations (Bovensiepen *et al.*, 1999), which is a reasonable value concerning $T^\star(\mathrm{Co})$. The Co magnetization vanishes in a similar way compared to the Ni one in cases where the T_C of Co is larger than the Ni one (Ney *et al.*, 1999): i.e. we see no 'tail' at higher temperatures in the magnetization curve within the experimental noise.

Due to the fact that the ground state moment of Co is larger than the Ni one, the element-specific $M(T)$ curves for Co and Ni cross each other at about 70 K close to $T^\star(\mathrm{Co})$. Above $T^\star(\mathrm{Co})$ we obtained that the shape of $M(T)$ for Ni is identical for the bi- and trilayer systems. This means that the direction of Ni magnetization in-plane is the same for both systems. Interestingly, as Co $M(T)$ sets in, the Ni $M(T)$ in the trilayer increases continously up to 136 % of $M(T = 45\mathrm{K})$ of the bilayer. This can be clearly seen from the XMCD spectra in Fig. 1(a). Concerning the fact that Co is ferromagnetic below $T^\star$, this effect is due to J_{inter}. Two main reasons may justify this behaviour. The first one is that the Ni $M(T)$ is enhanced by J_{inter}. The second one, which is the most likely reason, is that the J_{inter} forces Ni and Co to be aligned ferromagnetically. Therefore Ni $M(T)$ rotates from [1 0 0], the easy magnetization axis for 4 ML Ni (Schulz, 1995), to [1 1 0], the one for Co. This is illustrated in Fig. 1(b).

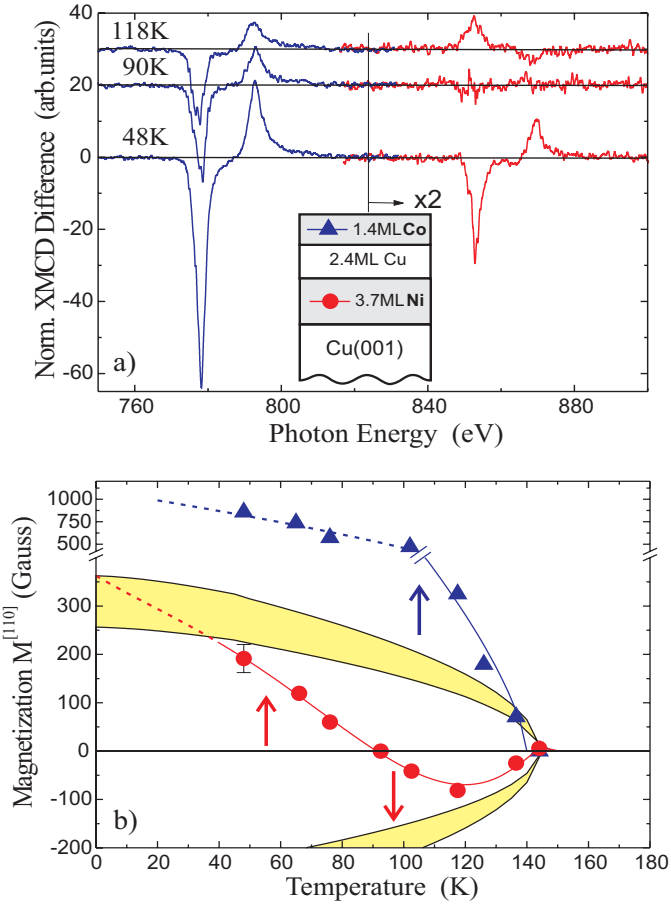

Figure 2
a) XMCD spectra for Co and Ni in the trilayer at different temperatures. **b)** Remanent magnetization curves measured along the [110] for Co and Ni as a function of temperature. The Ni magnetization changes sign due to antiferromagnetic alignment of both ferromagnetic layers. The lines are guides to the eye.

In Fig. 2(a) we show temperature-dependent XMCD spectra from a similar trilayer to the one of Fig.1. The Co and Ni thickness were selected in such a way that the two films have the same T_C while the Cu spacer was selected to be at a thickness where the J_{inter} is near to a crossover from ferro- to antiferromagnetic coupling, see Ney *et al.*, 1999. Interestingly, an unusual situation is realized, namely the Ni spectra are parallel to the Co ones at lower temperatures (up to 90 K) and then they change sign. This is illustrated better in Fig. 2(b) where the remanent magnetization of Ni is gradually reduced crossing zero. Then, it increases again until it vanishes at T_C (at about 140 K). The remanent magnetization of Ni is always reduced with respect to the values expected for [110] or [100]. The latter values taken from Fig. 1(b) are plotted by solid lines and the area in-between is shaded for a better overview (Fig. 2(b)).

An apparent interpretation of the reduced magnetization of Ni might be a multidomain state. However, multidomain states are inconsistent with in-plane magnetized films (Allenspach, 1994). We suggest that the Ni magnetization vector rotates away from the

easy axis. The smooth temperature decrease of the remanent magnetization further supports this interpretation. Then, the absence of a dichroic signal at 90 K indicates that the whole magnetization of Ni is 90° away from the [110] and it forms angles larger than 90° with the Co magnetization at higher temperatures. The only reason for such almost antiparallel orientations at higher temperatures is an antiferromagnetic interlayer exchange. Note that we have already reported an antiferromagnetic coupling for similar trilayers with 2.2 ML Cu-spacers, Ney *et al.*, 1999. The Cu spacer of the present trilayer is about 2.4 ML. This is at a Cu-thickness dependent crossover from anti- to ferromagnetic interlayer exchange, Ney *et al.*, 1999 . Therefore, the strength of J_{inter} should be rather small. Since J_{inter} does not change sign with temperature (Hathaway, 1994), it is the competition between an antiferromagnetic J_{inter} and magnetic anisotropies and/or higher order coupling mechanisms (biquadratic coupling, Demokritov, 1998) that could stabilize an almost parallel Co and Ni sublayer magnetization state at lower temperatures. In such a case J_{inter} may be estimated to be of the same order of magnitude with the small in-plane anisotropy of Ni, i.e. a few μeV/atom. An extensive discussion of these mechanisms goes beyond the scopes of this short contribution and for more details see Poulopoulos *et al.*, 1998 and references therein. Note, however, that compared to Poulopoulos *et al.*, 1998, in this work we succeed to realize a magnetic switch with a gradual rotation of the sublayer magnetizations and 90° orientations at a temperature of 90 K.

4. Conclusions

In this work we study via XMCD, for the first time, Co/Cu/Ni trilayers with the ordering temperature of Co being lower than the one of Ni. The main observations may be summarized as follows: The Co magnetization is larger than the one of Ni at $T = 0$ K. Co has a lower ordering temperature than the Ni and its magnetization is vanishing in the presence of ferromagnetic Ni. Within the experimental error no tail in the vanishing Co magnetization may be identified. Co forces the magnetization of Ni to be aligned parallel to it and an in-plane reorientation of the Ni magnetization occurs near at the ordering temperature of Co. Above this temperature no difference between the magnetization of Ni in the bilayer and in the trilayer is observed. Finally, an unusual case where the Ni magnetization rotates smoothly from parallel (at low temperatures) to perpendicular (at 90 K) and antiparallel (higher temperatures up to T_C) to the Co one is presented and discussed.

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