J. Synchrotron Rad. (1999). **6**, 699–700

Magnetism of thin films and in Fe/Ni, Co/Fe bilayers on Cu(001)

Fabrice Wilhelm,[a] Pankaj Srivastava,[a] Heiko Wende,[a] Andreas Ney,[a] Nils Haack,[a] Gustavo Ceballos,[a] Michael Farle[a] and Klaus Baberschke[a]*

[a]*Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany. Email:bab@physik.fu-berlin.de*

Using X-ray Magnetic Circular Dichroism, the spin and orbital magnetic moments were determined through the sum rules for ultrathin (2-4 ML) films of 3d elements on Cu(001). The fct Co ultrathin films, contrary to the fct Ni, show an enhancement of the orbital moment. The influence of direct coupling in Fe/Ni and Co/Fe bilayers is investigated. In Fe/Ni, an enhancement of the Ni (15 ML) orbital moment is observed. The easy axis of the Fe (3 ML) magnetisation changes from out of plane to in plane by capping it with Co.

1. Introduction

The determination of spin and orbital magnetic moments is important in order to understand the macroscopic magnetic properties of matter. For bulk 3*d* transition-metals (TM), these quantities have been calculated (Hjortstam et al. 1996) and found to be in good agreement with experiment (Chen et al. 1995). The reduction of the dimensionality modifies the magnetocrystalline anisotropy, spin (M_S) and orbital (M_L) moments due to the reduced symmetry at the surface and the structural change. In the present contribution, the X-ray magnetic circular dichroism (XMCD) measurements have been reported for thinner and thicker 3*d* TM single layer (Co and Ni) on Cu(001). Using the sum-rules (Thole et al. 1992, Carra et al. 1993), M_S and M_L can be determined separately. The influence of direct coupling on the magnetic properties of Fe, Ni and Co is investigated in Fe/Ni and Co/Fe bilayers.

2. Experimental details and data analysis

The experiments were performed at the SX700 monochromator beamlines at BESSY in Berlin. All the samples were grown *in situ* at room temperature on Cu(001) in an ultrahigh vacuum chamber. The $L_{3,2}$-edge spectra were recorded in the partial electron yield mode. The XMCD spectra were taken by keeping the helicity of the incident light fixed and reversing the direction of the remanent magnetisation by means of a pulse driven electromagnet. The Co and Ni films on Cu(001) were measured at 40 K. The spectra were corrected for the saturation effects (Hunter Dunn et al. 1995) and the background XMCD signal between L_3 and L_2 edges was subtracted to avoid the 4*s* electrons contribution. In order to know precisely the degree of circular polarisation, the 50 ML thick Co film on Cu(001) was used. By fixing M_S=1.55μ_B (Chen et al. 1995) and applying directly the second sum rule, P_C was found to be equal to 0.73 (theoretically 0.7). From the first sum rule M_L was determined to be 0.142±0.01μ_B. For this, the number of *d* holes was taken to be 2.43 (Guo et al. 1994) and a step function of 2:1 was used. The value of M_S was determined after subtracting the spin magnetic dipole term (T_Z) (Wu and Freeman, 1994) and adding the 4*s* and 4*p* contributions to the spin moment (Hjortstam et al. 1996) which is in total -1.8% for Co bulk, +5.5% for thin Co, +1.6% for Ni bulk and -10% for thin Ni. For thin films, all these contributions come mostly from the surface. The change in the number of *d*-holes with the thickness was taken into account (Srivastava et al. 1997).

3. Results and Discussion

3.1 Spin and orbital magnetism of thin Co and Ni films

The Figure 1 shows the XMCD signals of 2.1 ML Co and 4.0 ML Ni in comparison with 50 ML Co and 15 ML Ni films on Cu(001) respectively. The easy direction of the remanent magnetisation is found to be in-plane for both Co and thin Ni films and out-of-plane for 15 ML Ni. For 2.1 ML Co on Cu(001), we found M_S=1.77±0.1μ_B and M_L=0.25±0.05μ_B. As earlier experiments predicted using the ratio M_S/M_L (Tischer et al. 1995), the orbital moment is enhanced by 70% compared to bulk and a relatively small increase of 14% was determined for the spin moment. This is in accordance with theoretical calculations (Hjortstam et al. 1996). The origin of this enhancement comes from the strong influence of the surface which has a reduced symmetry. In comparison with the bulk-like

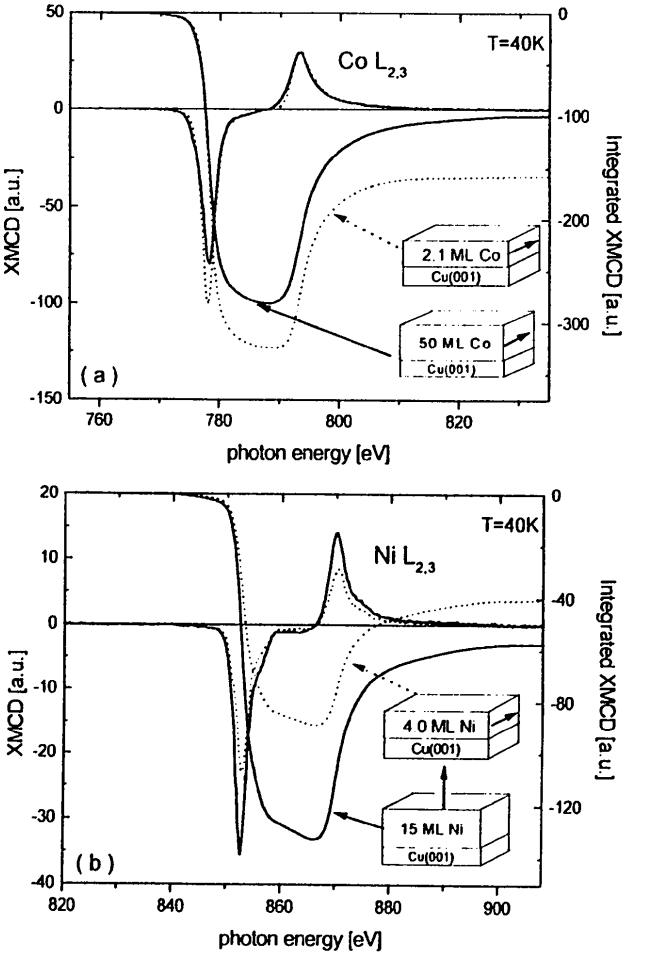

Figure 1. XMCD signals for (a) 2.1 ML (dotted line) and 50 ML Co on Cu(001) and (b) 4 ML (dotted line) and 15 ML Ni on Cu(001).

50 ML Co XMCD spectra, these contributions are mostly localised at the L_3-edge. For 4.0 ML Ni on Cu(001), we found M_S=0.24±0.1μ_B and M_L=0.035±0.01μ_B which are both reduced compared to bulk values (M_S=0.6μ_B and M_L=0.06μ_B). This effect is attributed to a stronger hybridisation between the Cu-*d*-Ni-*d* bands which tends to reduce the magnetic moments (Hjortstam et al. 1996) . In comparison to the 15 ML Ni XMCD signal, both the L_3 and L_2 intensities are reduced. For 15 ML Ni on Cu(001), the direction of magnetisation was found to be out-of-plane and M_S came out to be bulk like (0.61±0.1μ_B). However, the M_L was determined to be 0.075±0.01μ_B which shows an enhancement by 12% compared to the bulk value.

3.2 *Magnetism of Fe/Ni and Co/Fe bilayers*

By capping 15 ML Ni on Cu(001), it is possible to test if the weak orbital moment enhancement is due to the surface contribution. Therefore, we deposited 3.3 ML Fe on top of Ni. For both Fe and Ni, the direction of magnetisation stays normal to the surface which is in agreement with other measurements (O'Brien et al. 1996).

From Figure 2, one may see that there is no difference between the two XMCD signals of Ni uncapped and capped with Fe. Thus, both M_S and M_L of Ni are not influenced by Fe. Moreover, the M_L of Ni is enhanced throughout the film and it is not a surface effect. Therefore, the Fe capping has no measurable effect on the 15 ML Ni. For Fe, a small reduction of 10% (factor of 1.1) of the XMCD signal compared to 3.0 ML Fe on Cu(001) was observed.

In Figure 3, the XMCD signal of 3.0 ML Fe on Cu(001) uncapped and capped with 2.6 ML Co is shown. This 3.0 ML Fe has an easy axis of magnetisation out-of-plane. On depositing Co on top, the direction of magnetisation of Fe changes to in-plane. Similarly, 2 ML Fe on 10 ML Co on Cu(001) have the easy magnetisation axis in the film plane (O'Brien and Tonner, 1995). Compared to the bare thin films, the intensity of both XMCD signals are strongly reduced by a factor of 2.2. The origin of XMCD signal of Fe between L_3- and L_2-edges is not clear. It has been attributed to 4 sp, 3d and multi-electron excitations. For Fe, we found that the inter-edge region is affected by capping with Co (Figure 3 inset). The same effect appears for Fe on Ni (Figure 2 inset) and it may be attributed to direct coupling and hybridisation.

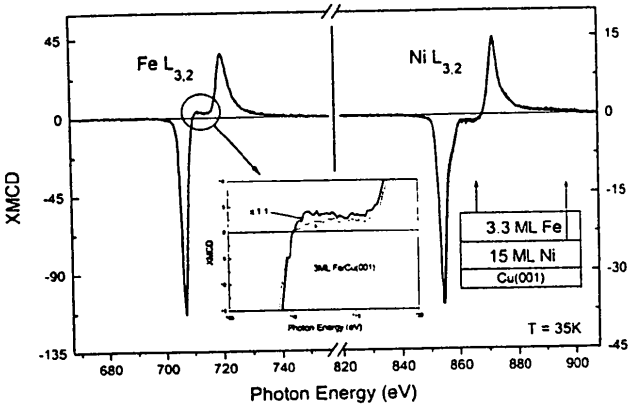

Figure 2. XMCD signal for Fe/Ni bilayer on Cu(001). In the inset, the dotted line is the XMCD signal for the thin Fe film on Cu(001) and the Fe capping layer is scaled to this one.

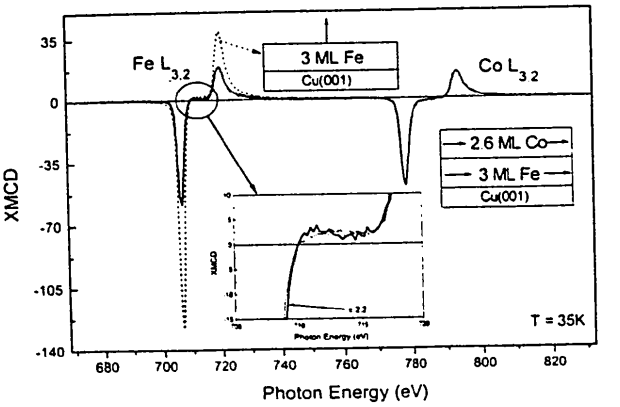

Figure 3. XMCD signal for thin Fe film on Cu(001) (dotted line) and for Co/Fe bilayer on Cu(001) (full line). In the inset, the Fe layer capped with Co is scaled to the uncapped one.

4. Conclusions

The orbital and spin magnetic moments are enhanced for 2.1 ML Co on Cu(001) and reduced for 4 ML Ni on Cu(001) compared to bulk. The orbital magnetic moment is shown to be weakly enhanced for an 15 ML Ni out-of-plane magnetised film on Cu(001). A reorientation of the magnetisation of thin Fe film on Cu(001) was found by capping with Co. The magnetic properties of both Fe and Co are effected due to direct coupling.

This work is supported by DFG SFB 290 and BMBF (05 SC8 KEA3) grants.

References

Carra P., Thole B.T., Altarelli M and Wang X.-D. (1993). Phys. Rev. Lett. **70**, 694.

Chen C.T., Idzerda Y.U., Lin H.-J., Smith N.V., Meigs G., Chaban E., Ho G.H., Pellegrin E. and Sette F. (1995). Phys. Rev. Lett. **75** ,152.

Guo G.Y., Ebert H., Temmerman W.M. and Durham P.J. (1994). Phys. Rev. B **50**, 3861.

Hjortstam O., Trygg J., Wills J.M., Johansson B. and Eriksson O. (1996). Phys. Rev. B **53**, 9204.

Hunter Dunn J., Arvanitis D., Mårtensson N., Tischer M., May F., Russo M and Baberschke K. (1995). J. Phys.: Conden. Matter **7**, 1111.

O'Brien W.L., Droubay T. and Tonner B.P. (1996). Phys. Rev. B **54**, 9297.

O'Brien W.L. and Tonner B.P. (1995). Surface Science **334**, 10.

Srivastava P., Haack N., Wende H., Chauvistré R. and Baberschke K. (1997). Phys. Rev. B **56**, R 4398

Thole B.T., Carra P., Sette F. and Van der Laan G. (1992). Phys. Rev. Lett. **61** , 1943.

Tischer M., Hjortstam O., Arvanitis D., Hunter Dunn J., May F., Baberschke K., Trygg J., Wills J.M., Johansson B. and Eriksson O. (1995). Phys. Rev. Lett. **75** , 1602.

Wu R. and Freeman A.J. (1994). Phys. Rev. Lett. **73**, 1994.

(Received 10 August 1998; accepted 14 December 1998)