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Conclusions

This chapter summarizes the presented work leaving also open questions for a future study of the FM/AFM interfaces or unanswered questions related with the Fe/CoO system.

In this work, the structural and magnetic properties of single-crystalline epitaxially deposited Fe/CoO thin films on a Ag(001) substrate were investigated. The epitaxial CoO thin films, up to a thickness of 13 ML, were prepared *in-situ* by co-deposition of Co in oxygen atmosphere. A substrate temperature of 450 K during deposition and subsequent annealing at 750 K lead to best crystallographic quality of the oxide. CoO films deposited in this way on Ag(001) exhibit sharp (1×1) Low Energy Electron Diffraction (LEED) patterns similar to the clean Ag(001) substrate. LEED *I(E)* experiments were performed to investigate the out-of-plane distortion of the lattice. The vertical interlayer spacing of the CoO films, deduced from a kinematic analysis of LEED *I(E)* curves, is $a_\perp/2$ = 2.17 Å, showing that the ultrathin CoO/Ag(001) layers are slightly expanded along the film normal as compared to the bulk structure, agreeing with other studies on the same system. The vertical distortion of the thin films is found to play an extremely important role in the electronic and magnetic properties of CoO.

Scanning tunneling microscopy (STM) was used to investigate the morphology of the CoO/Ag(001) system in the monolayer range, prior to and after annealing the sample in oxygen atmosphere. Before annealing, the CoO surface consists of islands with a typical height of 1-1.5 nm, which reduces by a factor of five after annealing. The STM images then show that only three atomic layers are simultaneously visible and provides an averaged size for the flat terraces of approximately 15 nm. These results prove that the growth recipe used in this work leads to flat CoO surfaces. The Fe layer deposited on top of the CoO reveals also relatively sharp LEED spots for the as-grown layers. No further annealing was carried out after depositing the Fe layer in order to keep the interface intact.

The macroscopic magnetic properties were studied by using the magneto-optical Kerr effect (MOKE). The Fe/CoO/Ag(001) samples show a characteristic increase of the coercive field when the system is cooled down from room temperature to 150 K. Clear discontinuities in the slope of the $H_c(T)$ curves at a temperature T_{AFM} are observed for 8 and 10 ML CoO thicknesses, and less clear for thinner layers. These discontinuities are attributed to the antiferromagnetic order transition of the CoO layer. The ordering temperature for the antiferromagnetic layer is thus in the same range as the Néel temperature for bulk CoO (T_N = 290 K). The easy axis of the Fe layer was found to be along the $\langle 110 \rangle$ directions of the Ag substrate.

The great sensitivity of synchrotron radition techniques such as X-ray Absorption Spectroscopy (XAS), X-ray Magnetic Circular and Linear Dichroisms (XMCD and XMLD) was employed to gain a deeper insight into the electronic and magnetic properties of the Fe/CoO/Ag(001) system with elemental selectivity.

Experiments were carried out on Fe/CoO bilayers as well as on single CoO films. Different measurement geometries were adapted in order to address the magnetic properties of the layers. For CoO/Ag(001) samples measured at grazing incidence, a huge linear dichroism (XLD) was found at room temperature. This is attributed to the structural vertical distortion of the CoO film. For normal incidence measurements, the XLD shows no signal, evidencing the fourfold symmetry of the film in the surface plane. For Fe/CoO samples at 150 K, the XMLD signal was measured at normal incidence. Because of the $\sin^2(\phi)$ dependence with the aximuthal angle ϕ and its dissapearance when heating the sample up to room temperature, it was concluded that the XMLD signal is purely of magnetic origin. Nevertheless, a structural contribution superimposed on the magnetic signal was also found, probably due to the a small misalignment of the sample surface with respect to the azimuthal rotation axis. By using the angular dependence of the X(M)LD signal, a separation of the overall XMLD signal in a structural and a magnetic part was successfully performed.

Furthermore, the results from spectroscopic XMCD and XMLD studies, combined with PhotoElectron Emission Microscopy (PEEM) measurements, provided complementary information that allowed us to completely characterize, both chemically and magnetically, the Fe/CoO interface.

Absorption spectra of Fe/CoO bilayers with different Fe thicknesses show only a weak indication of Fe oxide formation at the interface, estimated to be 0.3 ML of Fe. From the spectral shape, it is concluded that mainly an FeO-oxide type is formed. The relatively large XMCD signal at the Co $L_{2,3}$ edges proves the existence of a sizeable amount of uncompensated Co ferromagnetic moments aligned with the Fe magnetization. This layer is estimated to be 1.1 ML thick. Since the Co $L_{2,3}$ XMCD signal does not vanish at room temperature, it is concluded that these spins are located at the interface. The XAS spectral features typical of CoO are reproduced in the Co XMCD spectrum, indicating that the ferromagnetic Co spins at the interface maintian their oxidic character.

In order to fully exploit the use of XMCD- and XMLD-PEEM, an Fe

wedge was grown onto a continuous CoO layer, and different contrast mechanisms were used to image each layer separately. Whereas the Fe magnetic domain pattern was obtained by changing the polarization of the incoming light between left and right circularly polarized, in the case of the CoO layer, the X-ray energy was tuned to values with negative and positive XMLD contrast. The four-colour contrast obtained in the Fe XMCD images proves that the Fe magnetization can point along any of the $\langle 110 \rangle$ in-plane directions of the Ag(001) substrate. When the XMCD-PEEM images are taken for Co, a perfect replication of the Fe domain pattern is observed, again supporting the parallel coupling between $\mathbf{M}_{Fe}$ and the uncompensated Co spins. On the other hand, the Co XMLD-PEEM images show only a two-colour contrast, but prove the existence of antiferromagnetic CoO domains with domain walls coupled to the ones of the Fe layer. The two-colour contrast can be readily explained by the twofold symmetry of the antiferromagnetic order in the CoO layer. Finally, areas with very low or null Fe coverage displayed an AFM domain pattern with very small average sizes, which could not be quantified due to the limited lateral resolution of the microscope.

The magnetic coupling between the two layers was evidenced by azimuth-dependent experiments. Fe XMCD spectra at room temperature and at 150 K showed that the Fe magnetization directions are parallel to $\langle 110 \rangle$, in agreement with the MOKE results. On the other hand, the Co XMLD angular dependence showed that the Co spins point along any of the $\langle 110 \rangle$ in-plane directions. By making an analogy with recent experimental results and atomic multiplet calculations on Co/NiO systems, one can conclude that a parallel coupling exists between the Fe magnetization and the Co spin axes in the Fe/CoO/Ag(001) system. This parallel coupling can be explained by the relatively large amount of uncompensated Co spins at the Fe/CoO interface.