Chapter 7

Summary

This work presents the results obtained from various measurements on different Co/CoO and Co/Au/CoO EB multilayer systems containing ultrathin CoO layers, and related magnetic systems. The multilayer systems were deposited on H-Si(111) and Al_2O_3 substrates in a UHV chamber using Molecular Beam Epitaxy. The approximately 2 nm thick CoO layers were prepared using the controlled *in-situ* oxidation method developed by Gruyters *et al.* [GR00a]. *In-situ* and *ex-situ* characterization methods, such as AES, LEED, STM and X-ray-diffraction and TEM, have been used to determine the structural properties. STM measurements showed the samples to consist of granular Co and CoO layers. The fcc(111) oriented (LEED, X-ray-diffraction), round or elliptically-shaped Co and CoO grains have lateral diameters between 10 and 20 nm, depending on the substrate (STM). TEM measurements have shown an adequate separation of the individual layers within a multilayer. TEM imaging of a $[Co/CoO/AU]_{20}$ system revealed a structural waviness ("conformal roughness") of the multilayer which was replicated from the bottom to the top of the stack.

Knowing the structural properties of the samples, various magnetic properties have been studied using different measurement techniques.

The measurement techniques employed, such as SQUID magnetometry, Polarized Neutron Reflectometry (PNR) and Low Temperature Nuclear Orientation (LTNO) provide complementary magnetic information about the present layer systems.

First of all the EB systems, were subjected to SQUID magnetometry in order to determine their magnetization curves. This method provides a feasible way of observing the characteristic magnetic features related to the EB effect, such as the EB shift and the coercive fields. In a SQUID measurement, the magnetization of a sample is measured by averaging over the magnetic moments within the whole sample, projected onto the direction of the applied field.

One main goal in the present thesis was the study of the magnetization reversal processes in a $[Co/CoO/Au]_{20}$ multilayer using Polarized Neutron Reflectometry. SQUID magnetometry revealed the magnetic behavior of the multilayer systems to be similar to that of a comparable simple bilayer system. An asymmetric shape of the magnetization curves strongly suggests the magnetization reversal processes to be different on opposite sides of the hysteresis loops. Beyond this, the PNR technique is sensitive to in-plane rotations of the magnetization as well as to structural and magnetic periodicities along the direction perpendicular to the sample surface. The PNR measurements have proved to further elucidate the nature of the asymmetric reversal processes in the present system.

The second focus in this work was the exploration of the applicability of Low Temperature Nuclear Orientation for studying thin magnetic layer systems. This method, being a hyperfine field technique, is sensitive to the induced nuclear magnetization in a non-magnetic layer interface adjacent to a magnetic material. Using LTNO, Co/Au/CoO EB systems and related systems have been investigated in order to study how the EB effect expresses itself in the interfacial Au atoms adjacent to the magnetic layers. The method was successfully applied to the present layer systems and provides useful complementary results to be compared to conventional magnetometry measurements.

Study of magnetization reversal processes via Polarized Neutron Reflectometry

Using polarized neutrons, the scattered neutrons whose spin is not flipped and those whose spin is flipped after interacting with the sample magnetization can be detected separately. This spin analysis gives information about the average angle of the sample magnetization with respect to the applied field. Off-specular scattering experiments potentially provide additional information about magnetic domain sizes.

The present investigation on a $[Co/CoO/Au]_{20}$ multilayer reveals a drastic difference in the magnetization reversal processes on opposite sides of the same hysteresis loop. For the unbiased state (T = 300 K), reversal is due to rotation. For the biased state (T = 10 K), rotation is the dominant mechanism only for increasing fields. On the decreasing field branch, which is in the direction opposite to the bias (cooling field), the mechanism changes to domain wall motion. That is, for the EB state the AFM affects the reversal of the FM only in the direction opposite to the bias whereas for the transition back into the bias direction, the AFM appears not to have any significant effect. In a second field sweep, the magnetization of the sample seems to be trained. The magnetization reversal opposite to the pinning direction, i.e. for the decreasing field branch, has now become magnetic domain rotation. The reversal processes during the training cycle appear to be similar on both sides of the hysteresis loop.

First off-specular scattering experiments at fields close to the coercive fields were presented, and qualitative information on the relative domain size could be obtained from them.

During the magnetization reversal dominated by domain wall motion, off-specular scattering was observed to be limited to a region (in reciprocal space) close to the region of specular scattering, indicating the presence of relatively large domains. As opposed to this result, the reversals characterized by magnetization rotation reveal a large amount of diffuse scattering spread over a greater region in reciprocal space. This indicates the presence of a broader distribution of domains of different sizes.

In order to obtain more quantitative information from the off-specular scattering experiments, more detailed investigations will have to be performed.

The present results on a $[Co/CoO/Au]_{20}$ multilayer lead to a better understanding of asymmetric magnetization reversal processes for a type of EB system consisting of granular FM and ultrathin granular AFM layers, where the only prominant direction is the direction of induced EB.

Results obtained by SQUID magnetometry

The dependence of the EB effect in Co/Au/CoO trilayers on the Au spacer thickness was studied via SQUID magnetometry. A strong exchange bias between the antiferromagnetic CoO and the ferromagnetic Co layers across thin Au spacer layers has been observed even for a nominal Au thickness of 2.25 nm. For this thickness, the coupling strength amounts to as much as 0.1 erg/cm^2, a value usually obtained for a maximum coupling strength in a great many EB systems without a spacer. A detailed structural analysis of the present system confirms the complete separation of the FM and AFM layers by the spacer. This result supports the assumption that the origin of EB is not necessarily a nearest-neighbor (direct exchange) or next-nearest-neighbor (superexchange) coupling mechanism. However, there is no evidence for any oscillatory coupling as has been suggested by [Mew00]. A long-range exchange coupling extending to a distance as much as 5 nm, as was reported by Gökemeijer *et al.* [GAC97] was not observed. Contrary to that report, the strength of the EB effect is rapidly suppressed in the present Co(16.4 nm)/Au(x)/CoO(2 nm) trilayers until it completely vanishes for a 2.5 nm thick Au spacer.

Investigations of nuclear magnetic polarization in thin multilayer systems by Low Temperature Nuclear Orientation

In the present work, it was shown that LTNO is well suited to study the induced polarization of the Au nuclei in Co/Au/CoO EB systems. The EB effect was observed in the interfacial Au atoms of the spacer, where the magnetic Au moments seem to simply follow the Co moments during the magnetization reversal processes.

In magnetic saturation at 500 mT, the Au nuclear moments were found to be canted away at an angle Θ_{Au} from the Co moments and from the applied field axis. The canting was assumed to originate at the CoO/Au interface, since investigations on a simple Co/Au/Co trilayer revealed collinear alignment of the Au and Co moments at the Co/Au interface. On the other hand, measurements on CoO/Au/CoO trilayers have shown that the axis of nuclear alignment of the Au at the CoO/Au interface is strongly canted away from the applied field axis. While the interfacial Au moments revealed nuclear alignment, the Co moments in the CoO layer on average appeared not to be aligned. However, nuclear alignment of the Au moments at the CoO/Au interface implies that at least the interfacial CoO must be partially aligned. The partial alignment at the CoO interface may be attributed to the existence of uncompensated moments at the CoO interface as were experimentally found by [GR00b]. Following the model for EB in granular FM/AFM systems, proposed by Stiles *et al.* [SM99b], these moments act as possible centers for the nucleation of domain walls in CoO. This model does not necessarily imply collinear alignment at an FM/AFM interface.

The observation of a canting angle Θ_{Au} at the CoO/Au interface imposes the question of whether the alignment of moments at the Co/CoO interface in a simple bilayer would also be non-collinear. An LTNO experiment on a similar simple Co/CoO bilayer however could not resolve the interfacial alignment without additional (other than Co) radioactive probe atoms located at the interface.

The potential of LTNO for investigating magnetization reversal processes in a degree of detail not obtained from conventional magnetometry techniques has been demonstrated in this thesis. Observing the nuclear magnetization in the FM layers and the induced nuclear alignment at the adjacent non-magnetic spacer interface provides unique information about the reversal mechanisms in this type of FM/spacer/AFM exchange bias systems.

The present results on magnetization reversal processes by means of LTNO on EB systems qualitatively confirm the results obtained from a PNR study on a $[Co/CoO/Au]_{20}$ multilayer consisting of individual Co/CoO bilayers separated by relatively thick Au layers.

In this work, results on different EB systems containing granular Co and ultrathin granular CoO layers were presented; the present systems are characterized by a strong exchange bias anisotropy. Using different measurement techniques and slight variations of the composition of the EB system, such as the introduction of a non-magnetic spacer between FM and AFM, provides additional results and gives useful information to further elucidate the microscopic origin of the EB effect.