7 Conclusion

In the present work the spin-reorientation transition of ultrathin Ni$_x$/Cu(100) and Fe$_y$/Ni/Cu(100) films was investigated as a function of the layer thickness x and y, respectively, at 300 K in UHV. One aim of this thesis was the clarification of the question, whether the SRT of Ni/Cu(100) represents a phase transition of first or second order. Another aim was the characterization of the SRT of Fe/Ni bilayers on Cu(100), whose individual layers $-$Fe/Cu(100) and Ni/Cu(100)$-$ exhibit an opposite SRT. By imaging the magnetic domain microstructure during the film growth by means of spin-polarized low energy electron microscopy (SPLEEM), it was shown that the SRT of ultrathin Ni/Cu(100) films is a transition of second order, i. e. the magnetization reorients *continuously* within the large domains. In the Fe/Ni bilayers both a *continuous* reorientation of the magnetization and a simultaneous breakup of the large domains into *stripe domains* was observed. For both thin film systems the change of the magnetization direction during the SRT with respect to the orientation of the Cu substrate step edges was measured. The size of the domains and the width and the type of domain walls was determined. In the following the results for the studied systems are summarized separately.

In Ni/Cu(100) films the ferromagnetic order at 300 K sets in around 5 ML, in agreement with previous experiments. The size of the in-plane magnetized domains is typically on the order of some 10 μm without a systematic correlation of the domain walls to the step edges of the Cu substrate. The large size of these domains, compared to the ≈165 nm wide stripe domains at the onset of the ferromagnetic order in Fe/Cu(100) films at 2.2 ML, is due to the in-plane orientation of the magnetization of ultrathin Ni/Cu(100) films. Whereas Fe monolayers have a perpendicular magnetic anisotropy, and their magnetic stray field energy is minimized by a stripe domain state, the magnetization and thus the stray field of the Ni/Cu(100) film lies in the plane, i. e. in the orientation where the stray field energy is minimum. In-plane magnetized Ni films are observed in the thickness range of $5-9$ ML. The domain walls, which separate antiparallel magnetized domains, are 180°-Néel walls. These show the typical profiles of Néel walls, consisting of a core with two symmetrically extended logarithmic tails. For an 8 ML Ni/Cu(100) film such a profile yields a wall width of ≈400 nm. No systematic differences in the domain structure of Ni films grown and measured at 300 K and Ni films grown and measured at 100 K were found. At the beginning of the SRT at 300 K, which takes place around 9.5 ML Ni/Cu(100), an *elongation* of the original domain walls and spontaneously, reversely magnetized areas ($>1 \times 1$ μm^2) occurred within the large domains. These observations are due to the decrease of the domain wall energy density, which originates from a decreased effective anisotropy at the SRT. The observed *broadening* of the domain walls is also a result of the decreased effective anisotropy. The SRT proceeds *continuously* from an in-plane oriented magnetization to an orientation of the magnetization perpendicular to the film surface with increasing Ni layer thickness. Canted magnetization vectors within the domains are unambiguously verified by imaging the three components of the magnetization. The reorientation of the magnetization takes place via a *spiral-like* motion from the orientation of the magnetization parallel to the Cu step edges to the orientation perpendicular to the steps and perpendicular to the surface.

In Fe/Ni/Cu(100) films the orientation of the individual magnetizations of the Fe and the Ni layer was determined by XMCD and element-specific hysteresis loops as a function of the Fe layer thickness at 300 K. These measurements show, that the individual magnetizations are aligned parallel to each other during the SRT, thus indicating a ferromagnetic coupling between the Fe and the Ni film. The determination of the magnetic moments per Fe and Ni atom in perpendicularly magnetized Fe/Ni/Cu(100) films by means of XMCD at 300 K yields a reduced magnetic moment per Fe atom of ≈1.7 μ_B for 1 ML Fe at the Fe-Ni-interface. In 4 ML Fe on Ni/Cu(100) a high-spin state of Fe according to the Slater-Pauling curve was found. This finding implies that the Fe layers grow in the face-centered-cubic structure up to at least 4 ML on the Ni surface. The SRT takes place from an orientation of the magnetization perpendicular to the surface for uncovered Ni/Cu(100) films (7-11 ML) to an orientation of the magnetization parallel to the surface by a *spiral-like* motion with increasing Fe coverage. In this reorientation process the in-plane component of the magnetization rotates from “perpendicular to the substrate steps” towards “parallel to the steps”. *Simultaneously* to this motion, the domains break up into approx. 180 nm wide *stripe domains* within the interval of the magnetization reorientation ($2.5 - 2.9$ ML Fe). The stripe domains are aligned parallel to the Cu step edges, and the magnetization is found to *continuously* rotate within the stripes. The easy in-plane axis of the magnetization of the coupled bilayer system is the [001] direction, which also is the easy axis in bulk Fe. A straight domain wall with a random orientation to the Cu steps was observed to form rectangular protrusions at the start of the SRT. These elongated wall segments were found to turn toward the step edges, where they remained pinned until the stripe domain pattern was formed with increasing Fe layer thickness. At the maximum density of stripe domains a Bloch to Néel wall transition occurs within a narrow thickness interval of about 0.1 ML Fe.

From the average critical Fe layer thickness of the SRT, i. e. under the assumption of a *discontinuous* reorientation transition, the Fe-Ni interface anisotropy is determined to be -93 μeV/atom, by using literature values for the volume, the surface and the shape anisotropy contributions of the individual Fe and Ni layers grown on a Cu(100) surface. It was shown, that the increase of the shape anisotropy of the Fe/Ni/Cu(100) film by the increase of the Fe coverage, alone, is not sufficient to explain the observed SRT. In fact, the Fe-Ni interface anisotropy provides a decisive contribution to the reorientation of the magnetization into the film plane. Taking the *continuous* reorientation of the magnetization into account, a negative effective fourth-order anisotropy constant K_4^{eff} of the bilayer system is determined from the Fe thickness dependence of the tilt angle of the magnetization. At the same time the sum of the anisotropy contributions of second order yields $K_2 - K_d > 0$. In agreement with theoretically developed stability diagrams of the easy axis of the magnetization in the anisotropy space (K_4 vs. $K_2 - K_d$), this finding characterizes the observed canted magnetization during the SRT. However, the simultaneously observed breakup of the large domains into stripe domains of a cosine-like profile is not predicted by theory.

Finally, the SRT of Fe layers grown on 1.5 ML Ni/Cu(100), which is paramagnetic at 300 K, is investigated. Clear deviations of the domain pattern as compared to those of ultrathin Fe/Cu(100) films were found. The most important results are itemized in the following. (i) The onset of the ferromagnetic order in Fe/Ni$_{1.5}$/Cu(100) occurs at a lower Fe layer thickness (≈1.35 ML as compared to ≈2.2 ML Fe/Cu(100)), and broader stripe domains occurred in the Fe/Ni bilayer due to the smaller magnetic stray field. (ii) A canted magnetization is observed in the Fe/Ni film at the occurrence of domains due to the negative Fe-Ni interface anisotropy. Qualitatively, the SRT takes place as observed for Fe layers on perpendicularly magnetized Ni/Cu(100) films, however, the critical Fe thickness of the SRT is increased by ≈0.6 ML. The average width of the stripe domains of ≈750 nm at the SRT is more than four times larger than those of Fe layers grown on perpendicularly magnetized Ni/Cu(100) films. This broadening of the domains is attributed to the smaller magnetic stray field of the bilayer due to the minor Ni layer thickness. Despite the very narrow width of the SRT interval of only 0.15 ML Fe, the domain images unambiguously show a *continuous* reorientation of the magnetization into the film plane, i. e. a second-order SRT. No correlation of the magnetization direction with the substrate step edges at the start and at the end of the SRT was found in this system.

The UHV-SQUID magnetometer, which has been built up in the framework of this thesis and offers the possibility to determine the absolute value of the magnetization of an ultrathin film *in situ*, was presented. First measurements of an Fe/GaAs(100) film were shown. The design of the UHV-chamber allows for measurements of the *same* sample by SQUID magnetometry and ferromagnetic resonance for the first time.