Introduction

The investigation of magnetic ultrathin films has made great progress over the last decades [1,2]. Of particular importance for both the basic research and with regard to possible applications in magnetic recording techniques is the influence of the temperature, the film thickness or the film composition on the direction of the magnetization. Spin-reorientation transitions (SRT), i. e. changes of the magnetization direction as a function of the above mentioned parameters have both theoretically [3–6] and experimentally [7–10] been investigated also to answer the question, if they are continuous or discontinuous phase transitions[1], or if they proceed via a breakup into a multi domain state, in which in-plane and out-of-plane magnetized domains coexist [4,11–14]. The orientation of the magnetization is determined by the magnetic anisotropy energy, which includes spin-orbit (magnetocrystalline and magnetostrictive anisotropy) and dipolar (shape anisotropy) induced interactions [15]. The so-called easy axis of the magnetization is given by the minimum of the sum of these contributions. In the case of an ultrathin film the magnetostatic energy (strayfield energy) is minimum for an alignment of the magnetization parallel to the surface [16]. Thereby, the magnetostatic energy competes with the magnetocrystalline anisotropy energy, which may comprise contributions, that favor an orientation of the magnetization perpendicular to the surface. Due to the high surface to volume ratio of ultrathin films ($1 - 10$ ML), the increased surface influence as well as the lattice distortion caused by the lattice mismatch to the substrate, give rise to large intrinsic anisotropies, which are otherwise small compared to the magnetostatic energy in the respective bulk materials. The different dependencies of the individual anisotropy contributions on the temperature T and the film thickness d implicate a relative change of the contributions upon varying the parameters T or d, which may cause a change of the direction of the magnetization and thus give rise to a spin-reorientation transition.

In general, the ground state of a ferromagnetic system is a domain state, which arises from the coexistence of the short-range exchange interaction and the long-range dipolar interaction. Due to the competition of these interactions the magnetic moments of a ferromagnet are aligned parallel to each other at a short distance and antiparallel at a large distance. Depending on the

[1] Although the SRT is generally accepted to represent a phase transition, the order parameter, which must vanish above the critical thickness or temperature, is not uniquely defined.

energy, which is needed to form domain boundaries, different sizes and various kinds of domain shapes such as stripes, bubbles or meanders occur [17]. Since the extensions of the magnetic domains and the domain walls vary with the thickness dependent anisotropies [18,19], a magnetic imaging technique is required, which provides the opportunity to resolve magnetic structures on the submicrometer scale *in situ* during the film growth with a high image acquisition rate, in order to study the formation of magnetic domains during the thickness-driven SRT. Simultaneously, all three components of the magnetization have to be detected to determine the magnetization direction during the SRT. All these requirements are achieved by spin-polarized low energy electron microscopy (SPLEEM) [20,21], which was used in this thesis to study the SRT of ultrathin Ni/Cu(100) [5,8,10,22–24] and Fe/Ni/Cu(100) [25,26] as a function of the thickness. Due to the energy of the electrons below 10 eV this method is surface sensitive and affords the correlation of magnetic structures to topographic features, such as atomic step edges and defects at the same time. The lateral resolution of ≈10 nm is suited for the investigation of domain walls, which typically have widths of $1 - 1000$ nm in thin films.

The spin-reorientation transition of ultrathin Ni/Cu(100) films proceeds from an orientation of the magnetization in the film plane to an orientation perpendicular to the plane as a function of increasing temperature or thickness. The reason for the reversed SRT of Ni/Cu(100) in comparison to other film systems, such as e. g. Fe/Cu(100) [27–32], is the negative surface anisotropy of Ni, which favors a magnetization orientation in the film plane and has the largest influence at low thicknesses. The positive thickness independent volume anisotropy, which arises from the tetragonal distortion of the lattice, is responsible for the orientation of the magnetization perpendicular to the surface above 11 ML [33]. The system Fe/Ni/Cu(100) represents the prototype of a ferromagnetically coupled bilayer system, in which the individual layers deposited on Cu(100) show an opposite SRT. Previous investigations revealed interesting magnetic properties of Fe/Ni/Cu(100) films of various thicknesses, such as a ferromagnetic Fe layer at the Fe/Ni interface beneath an antiferromagnetic Fe film in the thickness range of 5 to 10 monolayers (ML) Fe [25,26,34]. Recently, an exchange coupling between a ferromagnetic surface layer of the Fe film and the Ni film was observed [35]. The influence of the concentration x of Fe_xNi_{1-x} alloy films on the spin-reorientation transition was investigated lately [36].

The SRT of ultrathin Ni/Cu(100) films has been investigated so far by different techniques, i. e. x-ray magnetic circular dichroism [7], ferromagnetic resonance [37], magneto-optical Kerr effect [9] and second harmonic generation [10]. In all these techniques an external magnetic field is applied to saturate the magnetization of the film in different directions. Furthermore, the respective measured signal originates either from the whole sample or at least from a millimeter-sized region of the film. In this work, the micromagnetic domain structure of ultrathin Ni/Cu(100) and Fe/Ni/Cu(100) films is imaged during the SRT as a function of the thickness. These measurements provide an insight into the change of magnetic domains at the reorientation of the magnetization in the absence of an external magnetic field for the first time. The aim of this thesis is the clarification of the following main questions: (i) Is there a continuous SRT [10,22] or a breakup into a multi domain state at the SRT of Ni/Cu(100) films? (ii) Is the reorientation of the magnetization at the SRT affected by the step edges of the Cu(100) crystal? (iii) What are the typical scales of the domains and the domain walls of in-plane magnetized ultrathin Ni/Cu(100) films, and how do their sizes change at the SRT? (iv) Is the SRT of Fe/Ni/Cu(100) as a function of the Fe thickness a continuous one or does the SRT proceed via a breakup into stripe domains like in Fe/Cu(100) [12,38]? (v) How does the SRT take place in the individual Fe and Ni layers, and how does the Fe-Ni interface affect the magnetic moments per Fe and Ni atom? (vi) What are the dominant anisotropy contributions to the SRT?

A second aim of this thesis is the construction of a UHV-chamber and the setup of a high-T_c-SQUID magnetometer [39] in order to determine the absolute value of the magnetization of an ultrathin film *in situ*. The chamber should also allow for measurements of the ferromagnetic resonance (FMR) [40] of the *same* sample *in situ*.

The present work is organized as follows: In chapter 1 the fundamentals of ferromagnetism in coupled ultrathin films and both theoretical and experimental aspects of the spin-reorientation transitions of Ni/Cu(100) and Fe/Cu(100) films are introduced. Moreover, the occurrence of magnetic domains in ultrathin films is elucidated. Experimental details of the applied techniques, i. e. spin-polarized low energy electron microscopy (SPLEEM), x-ray magnetic circular dichroism (XMCD) and superconducting quantum interference device (SQUID), are presented in chapter 2. The substrate preparation and the growth of ultrathin films is summarized in chapter 3. The design of the UHV-SQUID is described in chapter 4. More technical details, drawings of the system and the computer program used for the data acquisition can be found in the appendix. In chapter 5 the analysis of the magnetic domain structure of Ni/Cu(100), Fe/Cu(100) and Fe/Ni/Cu(100) films is given. Finally, a detailed investigation of the spin-reorientation transitions of Ni/Cu(100) and Fe/Ni bilayers on Cu(100) is presented in chapter 6.