Chapter 1

Introduction

Magnetic nano structures are of great importance for modern applications. Hand in hand with the ongoing miniaturization of magnetic devices new questions of the magnetic behavior on the reduced length scale arise. In the last decades, the recording density has increased immensely by decreasing the size of magnetic areas in which information is stored (down to some 10 nm). This trend is still continuing and magnetic structures on the atomic scale are the aim. The imaging of magnetic arrangements at the nanometer or even atomic length scale is of fundamental interest as well [1, 2]. It provides insights into new and elementary behavior of magnetic phenomena.

In many magnetic devices, antiferromagnets in direct contact to ferromagnets play an essential role, though fundamental properties concerning the interplay between both are not fully understood. In the last years, spin-polarized scanning tunneling spectroscopy (Sp-STS) [3] and spin-polarized scanning tunneling microscopy (Sp-STM) [4] became powerful tools to investigate magnetic structures on the nanometer scale. Even antiferromagnetic surfaces can be imaged with these methods [5, 6]. In this work, Sp-STM is extended successfully to image a well-defined magnetic in-plane component [7]. This method was applied to study the behavior of magnetic frustration at the surface of thin antiferromagnetic films which are in direct contact to a ferromagnetic substrate [8].

The first prove that a magnetic body may consist of areas where the magnetization points in different directions was given by Barkhausen in 1919 [9]. Starting from this, new methods that allow the direct imaging of magnetic pattern in real space have been invented. Real space imaging methods have the advantage over methods working in the reciprocal space that they are capable to investigate non periodic and localized magnetic structures. With the development of the first methods, one of the main effort has always been to improve the resolution to be able to investigate smaller structures. Recently, the challenge has reached to image magnetic structures on the atomic scale [10].

Up to now, several techniques have been developed exploiting different physical effects and the most important are shortly introduced below. Magnetic imaging techniques can be divided into two groups. On the one hand, there are methods that map the local magnetic field which is emerging from the sample (local magnetic stray field). On the other hand, there are methods which investigate internal properties determined by the local magnetization. Since the interest typically lies on the local magnetization, the techniques investigating the magnetic stray field have the disadvantage that only a limited conclusion can be drawn to the arrangement of the local magnetization pattern.

The first real space picture of magnetic patterns was obtained by mapping the distribution of small magnetic particles (magnetic powder) arranged along flux lines of the local stray field by Bitter in 1932 [11]. Nowadays, a resolution of some 10 nm has been achieved with the Bitter-technique [12]. Another technique that is sensitive to the magnetic stray field is magnetic force microscopy [13]. Here, the magnetostatic interaction between a magnetic tip and the stray field of the sample is analyzed with respect to the lateral tip position. This method belongs to the well established magnetic imaging techniques because of the simplicity of operation and the easily achievable high lateral resolution between 20 and 100 nm [14]. One technique that is sensitive to the local magnetization components is the magneto-optic Kerr microscopy [15]. This method analyzes changes of the polarization of light caused by the reflection from a magnetic sample surface. The lateral resolution is limited by the wave length of the light. By performing so-called near field microscopy measurements the resolution was enhanced to below 200 nm [16–18]. Various types of electron microscopes have been developed which analyze electrons emitted, reflected from, or transmitted through a magnetic sample. One important method is scanning electron microscopy with polarization analysis (SEMPA) [19]. Here, a focussed high energy (keV) electron beam is scanned over a sample surface and the emitted low-energy secondary electrons are analyzed with respect to their spin. The spin reflects the local magnetization of the sample near the surface. This method allows the measurement of all three spatial magnetization components and the reflectivity of a sample surface, independently. A lateral resolution better than 10 nm has been achieved, recently [20–23]. Another technique, the so called photoemission electron microscopy has the additional advantage that the magnetic structure can be imaged element specifically by exploiting the different absorption energies of core-level electrons. Thus, it is possible to address element specific magnetic layers within multilayered structures and in alloyed films [24]. All these methods yield insight into micromagnetic phenomena and will do so in the future. However, there is need for techniques with a higher lateral resolution.

Binnig and Rohrer's [25] development of scanning tunneling microscopy (STM) allowed to image the topography of a sample surface with atomic resolution [26]. Since than the question arose wether the analysis of the electron spin can be used to map magnetic structures on the atomic scale as well. This idea was first mentioned by Pierce [27]. He suggested to use the effect of tunneling magneto resistance discovered in 1975 by Jullière [28]. Jullière showed, that the tunneling probability between two ferromagnetic electrodes separated by an insulator depends on the relative orientation of the magnetization of both. The first pioneering works on Sp-STM experiments have been performed in the beginning of 1990. In these experiments, the spin-dependent tunneling current between ferromagnetic tips and magnetic samples was measured in air [29] and under vacuum [30], but it was not possible to separate the topographic and magnetic information. A further, but unsuccessful development was to try to separate the magnetic information from the topography by using optically pumped semiconducting GaAs tips [31–33].

Recently, the attempt to investigate the spin-dependent tunneling current between a ferromagnetic tip and magnetic samples received new interest. As already mentioned, two successfully experimental approaches have been developed which allow the separation of magnetic and topographic information. Bode and coworkers developed Sp-STS [3] to image the magnetic structure of a sample surface and Wulfhekel and coworkers designed a Sp-STM [4]. Both techniques allow imaging of magnetic structures with a high lateral resolution of at least 1 nm [34, 35].

In thin films and at the surface of bulk samples, the magnetization lies often in the plane of the surface because of shape effects (shape anisotropy). Therefore, it is of high interest to investigate a well-defined in-plane component of the magnetization with the Sp-STM. As shown in this work, this is achieved by the proper choice of the Sp-STM electrode [7]. In our approach, we use ferromagnetic rings instead of conventionally sharp tips as STM-electrodes. A high lateral resolution of 1 nm has been achieved using these rings, comparable to the resolution achieved for the out-of-plane component.

The advantage of Sp-STM measurements is that changes in the electronic structure can be separated clearly from the magnetic signal which allows the investigation of alloys and of systems having unknown electronic structures. Also a well-defined in-plane component of the magnetization was imaged whereas in Sp-STS only one random in-plane component can be measured.

In the following chapter, a short overview is given on the static behavior of magnetic phenomena. The focus lies on combined systems consisting of a ferromagnet that is in direct contact with an antiferromagnet. The principle of tunneling, STM and the extension to Sp-STM are introduced in the last part of chapter 2. The experimental setup, the realization of Sp-STM measurements and the preparation of Sp-STM ring electrodes are described in the first part of chapter 3. To confirm the imaging of a well-defined in-plane component, the method was tested on Fe-whiskers which have well known magnetic patterns (second part of chapter 3). The capability of high lateral resolution of Sp-STM is used to investigate local magnetically frustrated regions down to 1 nm, formed in thin antiferromagnetic Mn films grown on Fe(001). The magnetic frustration within Mn films is caused by interface roughness of the underlying Fe substrate and was imaged at the Mn film surface (first part of chapter 4). It was found that the measured size and sign of the spin contrast strongly depends on the bias voltage (second part of chapter 4). The results obtained on thin Mn films on Fe(001) are discussed in chapter 5. The magnetically frustrated regions are compared to simple continuum approximations and to calculations performed on the basis of a Heisenberg model. For the understanding of the voltage dependent spin contrast the experimental data are discussed in the framework of theoretical calculations.