1. Introduction

The phenomenon of magnetism was already discovered in the antique by the Greek and the Chinese. They knew that loadstone attracts iron but indications that magnets have two poles were found only in chinese scripts [1]. In the middle ages almost no deeper insight into the properties or the origin of magnetism was obtained. This changed in the Renaissance with the renunciation from alchemy and the development of the modern sciences. Systematical studies were performed and the knowledge increased but it lasted until the beginning of the 19^{th} century when M. Faraday and H.C. Oersted showed convincingly that magnetism is related directly to current flows and therefore to moving charges. A variety of discoveries followed and eventually Maxwell developed his unified field theory for the electromagnetism in 1864. The idea that the electron is an elementary particle developed in the outgoing 19^{th} century and was confirmed experimentally by J.J. Thompson in 1897. With the development of quantum mechanics it became apparent that quantization is a general phenomenon in physics. One experimental evidence was found in the quantization of the angular momentum in atoms by O. Stern and W. Gerlach in 1921. G.E. Uhlenbeck and S.A. Goudsmit found out in 1925 that electrons have an additional spin. This spin is related directly to the magnetic moment and W. Heisenberg could explain ferromagnetism in solid states as a collective coupling of the electron spins.

Even though the principle ideas of ferromagnetism are understood since the 1920s, there is still increasing interest in magnetic systems. The reason for this lies in the diversity of effects and material systems that show magnetic behavior. The advancements in experimental techniques, e.g. synchrotron-light sources, scanning-microscopy techniques, cryo techniques for temperatures down to the sub-milli Kelvin range, and many more, offer the possibility to investigate magnetic samples under various conditions. Thus, by using complementary techniques insight into the complex ferromagnetic systems can be gained from different perspectives.

For applications the possibility to exploit the non-volatility of the magnetization in small magnetic particles for information storage has been recognized early and magnetic core memories have been used in the 1950-1970s in the first computers. From these days the development of semiconductor-based processors and non-volatile storage units took place separately. The processor development was triggered by the invention of the transistor in 1947 by J. Bardeen, W. Schockley, W. Brattain [2, 3] and follows Moore's law, i.e., doubling the number of transistors of a processor approximately every 18 months. This could be realized by decreasing the lateral sizes and using improved materials and techniques. On the other hand, magnetic thin film techniques have been optimized for the application in hard disks. Storage densities of up to 100 $\mathrm{Gbit/in^2}$ are realized today in laboratory prototypes [4].

The integration of these two development directions to devices combining the advantages of both technologies is the next step. First applications are the Magnetic Random Access Memories (MRAM) [5]. Here, the non-volatility is combined with silicon processor technologies for fast storage cells. These devices are based on the giant magnetoresistance (GMR) [6, 7] or the tunnel magnetoresistance (TMR) effect [8].
In recent years, investigations of the resistance contributions in ferromagnets have attracted a lot of interest because new physical effects have been predicted. For very high current densities domains and domain walls can be influenced and moved. This effect may allow faster switching cycles compared to the switching fields that are generated by the traditional "bit-line" concept.
Further developments are still under consideration. The idea of a transistor that uses the electron spin [9] instead of its charge is widely discussed. Magnetic semiconductors [10] are a material class with promising properties for applications. Combining electron transport with optical data transmission in semiconductors illustrates a further development with a high potential for fast data processing and storage on a single chip. First approaches towards a quantum computer using the electron spin are also discussed and predicted to generate computational performances beyond traditional expectations. First experimental realizations of coupled "qubits" have already been demonstrated [11], but the large-scale integration of "qubits" is still a challenge.

The contribution of this experimental work to the rapid development in magnetism consists of three main topics. First, the study of the magnetization in magnetic rings is an example of the complexity of magnetic systems. By Hall micromagnetometry and magnetic-force microscopy (MFM) different magnetic configurations are observed and can be verified by numerical simulations. It is shown that the magnetic configurations and switching processes can be controlled by the geometry of the rings. All configurations survive up to room temperature and thus make them interesting for storage applications. Secondly, magnetoresistance experiments are performed on different microstructured magnets. The resistance contributions in micromagnets are investigated and from transport experiments conclusions concerning reversal mechanisms are drawn. At third, microstructured ferromagnets are combined with semiconducting heterostructures to so-called hybrid devices. This approach aims at the efficient injection of spin-polarized electrons into semiconductors.

This thesis is organized as follows: The second chapter gives an overview of the basic physical concepts which are necessary to understand the experiments. Starting from the fundamentals of ferromagnetism the resistance contributions arising in ferromagnetic samples are discussed. Finally, models for hybrid devices with semiconductors are presented in which spin-polarized electrons are injected. The third chapter introduces material systems, preparation techniques, and the most important measurement techniques. Chapter 4 and 5 summarize the results of the investigations on microstructured rings and ferromagnetic rectangles, respectively. In chapter 6 the experiments on hybrid devices are presented followed by a discussion of the difficulties and possible future approaches. Conclusions can be found in chapter 7.

2. Basic physical concepts

This chapter deals with the main concepts of magnetism. The microscopic origin and the description of micromagnetic systems are discussed by means of numerical simulations.The anisotropic magnetoresistance and domain-wall contributions to the resistance have to be considered for the understanding of magnetoresistance measurements of microstructured ferromagnets. Finally, the combination of ferromagnets and semiconductors to hybrid devices is presented theoretically for the two borderline cases, i.e., with perfectly clean interfaces and with integrated tunnel barriers.

2.1. Principles of micromagnetism

Magnetism is a quantum mechanical effect based on the coupling of electron spins. In ferromagnets a collective and parallel orientation of the spins and therefore of the magnetic moments is the consequence. Beside this, external magnetic fields, magnetic stray fields, and the crystal structure affect the orientation of the magnetization in the solid state. The important energy terms are described in the following sections and the micromagnetic approach is introduced.

2.1.1. Ferromagnetism

Ferromagnetic materials have a finite magnetization in the absence of an external magnetic field for temperatures below the Curie temperature. In contrast to this, in diamagnetic and paramagnetic materials a magnetization must be induced by an external magnetic field. Microscopic descriptions are provided by the Heisenberg approach for localized spins and various band-models.
On the one hand, the model of localized spins assumes a lattice with fixed spins and corresponding magnetic moments. It was shown by Heisenberg [12] that a Hamiltonian of the form

$$H_{\mathrm{Heisenberg}} = -2 \sum_{\mathrm{i<j}} J_{\mathrm{ij}} \, \vec{S}_{\mathrm{i}} \cdot \vec{S}_{\mathrm{j}} \tag{2.1}$$

takes into account the Pauli exclusion principle correctly. $\vec{S}_{\mathrm{i}}$ and $\vec{S}_{\mathrm{j}}$ are the spin vectors at the lattice sites i and j and J_{ij} is the exchange constant. The exchange interaction has no classical equivalent and is a direct result of the Pauli exclusion principle and the fermionic character of the electrons. In Eq. (2.1) $J_{\mathrm{ij}} < 0$ results in an antiparallel orientation and $J_{\mathrm{ij}} > 0$ leads to a parallel one. The latter is the ferromagnetic orientation because the scalar product is maximized for parallel spins and a positive J_{ij} results in a reduction of the energy. In good approximation the model of localized spins is valid for metal oxides like Fe_2O_3 and MnO.

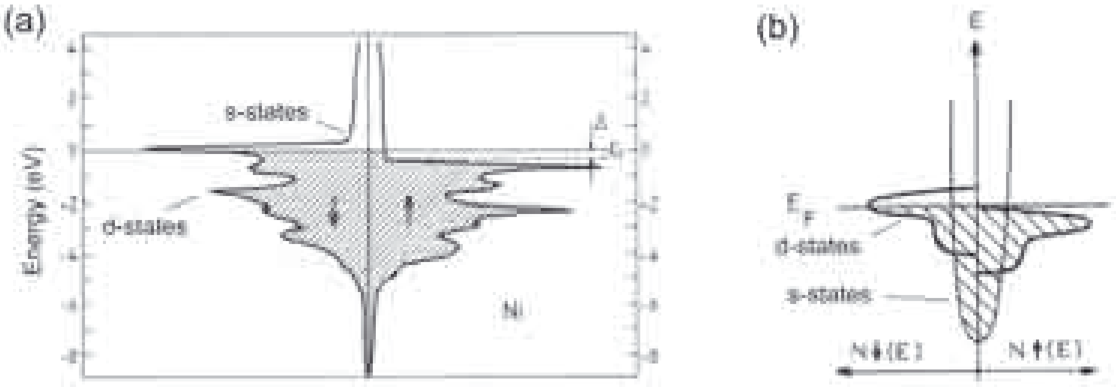

Fig. 2.1.: (a) Calculated density of states for Ni [13, 16]. (b) Schematic illustration of the 3d-band shifting [17].

On the other hand, the electrons in classical 3d-transition metals like Fe, Co, and Ni cannot be considered as localized because these materials are conductors with almost free electrons. Therefore, a band model [13, 14] is an appropriate description. Starting from atomic orbitals, the energy levels split into bands when combined to a crystal. In ferromagnetic materials the exchange interaction, also acting between free electrons, shifts the spin bands energetically. As a typical result of a band structure calculation the density of states is shown in Fig. 2.1 (a). A schematic is depicted in Fig. 2.1 (b) for a transition metal. The 4s-electrons with the maximum of the probability density farther from the nucleus are treated as almost free electrons whereas the 3d-electrons are assumed to be more localized. In a first approximation the exchange interaction only shifts the d-bands generating a spin imbalance (see Fig. 2.1 (b)). For details of band structure calculations see, e.g., Ref. [15]. The density of states can explain the most common magnetic properties. The magnetization results from the difference between the numbers $N_\uparrow$ and $N_\downarrow$ [18] of filled spin states:

$$M = g\,\frac{\mu_B}{V}(N_\uparrow - N_\downarrow). \tag{2.2}$$

Here, $\mu_B = \frac{e\hbar}{2m}$, V, and g are the Bohr magneton, the sample volume, and the electron g-factor, respectively.

The spin polarization is crucial in the discussion of hybrid devices and considers the density of states at the Fermi energy E_F, because only electrons in an energy range of $\Delta E \approx \pm k_B T$ around E_F contribute to the conductivity. Only these electrons can be excited thermally into free electron states. For electrons of lower energies the neighboring states are already occupied. Thus, often the spin polarization is considered as the normalized difference of filled states at the Fermi energy:

$$P_N = \frac{N_\downarrow(E_F) - N_\uparrow(E_F)}{N_\downarrow(E_F) + N_\uparrow(E_F)}. \tag{2.3}$$

For transport measurements this definition has to be modified and the densities of states $N_{\uparrow,\downarrow}(E_F)$

have to be multiplied by the corresponding spin-dependent Fermi velocity v_F [19, 20, 21]:

$$P_I = \frac{N_\downarrow(E_F)v_{F\downarrow} - N_\uparrow(E_F)v_{F\uparrow}}{N_\downarrow(E_F)v_{F\downarrow} + N_\uparrow(E_F)v_{F\uparrow}}. \tag{2.4}$$

2.1.2. Energy contributions in ferromagnets

The total energy of a micromagnetic system consists of different energy contributions

$$E = E_H + E_D + E_{EX} + E_K + E_0, \tag{2.5}$$

which will be reviewed shortly.
An external magnetic field $\vec{H}$ affecting a magnetic particle with the magnetization $\vec{M}$ results in the Zeeman energy

$$E_H = -\int_V \vec{M} \cdot \vec{H} dV. \tag{2.6}$$

The integration is performed over the volume V of the magnetic sample. The term is important for the simulations of hysteresis loops and can be controlled by external fields. The magnetization $\vec{M}$ generates a magnetic stray field $\vec{H}_S$ which influences the magnetization itself and is expressed in terms of a demagnetization energy

$$E_D = -\frac{1}{2}\int_V \vec{M} \cdot \vec{H}_S \, dV. \tag{2.7}$$

The exchange coupling mentioned above is generally written in the Heisenberg form

$$E_{EX} = -2\, J \sum_{i<j} \vec{S}_i \cdot \vec{S}_j, \tag{2.8}$$

with a lattice site independent exchange energy J.
The crystal anisotropy energy E_K describes the interaction of the magnetization with the crystal lattice. The analytical form depends on the specific crystal lattice. All other energy contributions like magnetostriction energy and energies resulting from lattice defects are combined in E_0 and are neglected for the investigations of this thesis.
Generally, in real micromagnetic systems domains can be observed which reflect the interplay of the energy contributions when minimizing the total energy. The exchange energy and the crystal anisotropy energy prefer a single-domain orientation because the energy is minimized for parallel magnetic moments which point in the direction of the easy axis, i.e., the axis of lowest energy for the magnetization. In contrast, the demagnetization term is maximized for a single-domain configuration because of the resulting strong stray field. Thus, this energy term favors a multi-domain configuration. Applying an external magnetic field allows to control the magnetic configuration of the micromagnet.