Chapter 1

Introduction

Information storage on individual atoms still remains a dream for our information society. Today's commercial applications require magnetic storage devices with bit densities unimaginable over 50 years ago, and this development still continues. Advances in technology led to smaller and cheaper computers using data storage technologies at much higher density. In today's commercial hard disks, one bit has the size of about 3600 nm^2, thereby allowing the storage of more than one TeraByte (10^6 MB) in a conventional 3.5" slot device.

The discovery of the *giant magnetoresistance* (GMR) effect in 1987 enabled to decrease the bit sizes down to today's dimensions. In 2007, Peter Grünberg and Albert Fert received the Nobel prize for their discovery of the GMR effect. When passed by a current, the conductance of a device consisting of two magnetic layers separated by a non-magnetic layer depends on the relative magnetization directions of the two magnets. To readout the magnetization at high lateral resolution, one magnetization is fixed whereas the other is affected by the strayfield of the sample. Depending on the magnetization of the sample, the conductance of the device is high or low, and this is decoded to the bit state "1" or "0".

One technique did not change over the past decades: Magnetization reversal is still based on the application of an external magnetic field that is generated by the Oersted field of an electric current. But the electrons that contribute to the current are not only charge carriers—they also have a spin and therefore a magnetic moment. Inside a non-magnetic metal, the spin of the electrons has no preferential orientation and therefore cancels on average. In 1996, Slonczewski [1] and Berger [2] predicted that the current flowing through magnetic multilayers could have a more direct effect on the magnetic state than the Oersted field: When the current passes through a ferromagnet, it becomes partially spin-polarized, aligning the electron spins along the magnetization direction of the ferromagnet. The current carries a net angular momentum, and if the thickness of a non-magnetic layer between two ferromagnets is small enough, the current can interact with the magnetization of the subsequent magnetic layer. The spin current exerts

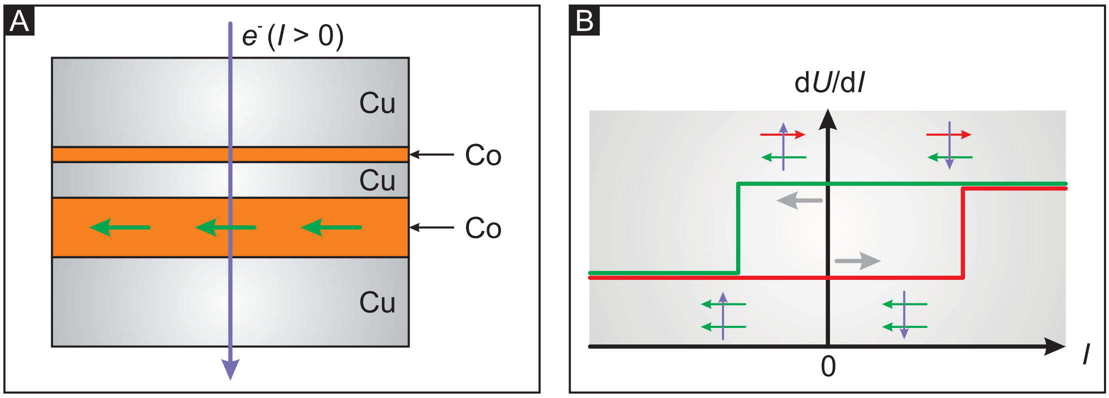

Figure 1.1: (**A**) Schematic of a pillar device used in the experiments by Katine *et al.* with two Co layers separated by a thin Cu layer [3]. (**B**) Ideal dU/dI signal of differential resistance of a pillar device exhibiting hysteretic jumps as the current is swept. The current sweeps begin at zero; red and green lines indicate increasing and decreasing current, respectively. Depending on the current direction, the magnetization of the thin Co layer switches to the parallel or antiparallel configuration.

a spin transfer torque on the magnetizations inside the multilayer device, and for large enough currents this torque leads to magnetic precession or even reversal. This is the basic concept of current-induced magnetization switching.

Since this prediction, many experiments have been performed that investigate spin transfer induced magnetization dynamics [3–17], using different device geometries like mechanical or lithographically fabricated point contacts, nanopillars or tunnel junctions. The first clear experimental verification of the spin-torque driven magnetization reversal has been published by Katine *et al.* [3]. They investigated the current-driven magnetization reversal in pillars containing two Co layers of different thickness separated by a Cu spacer, as depicted in Fig. 1.1A. When applying a low magnetic field to fix the magnetization of the thick layer in a one-domain state, spin-polarized electrons flowing from the thick to the thin layer can switch the magnetic moment of the thin layer parallel to that of the thick layer, while a reversed current leads to a switching into the antiparallel configuration, as illustrated in Fig. 1.1B. In general, the switching process can be described within a simple macro-spin model where all the magnetic moments within a particle rotate coherently. However, it was found that in some cases this model fails and has to be extended to the combined action of spin injection and the Oersted field that is induced by the current [18].

Although the lithographic fabrication of layered systems has been significantly improved, it is very hard to realize multilayer devices with atomically sharp interfaces without any intermixing of the different materials. Consequently, it is not clear where *exactly* the current flows that interacts with the magnetic electrodes, and due to the structure of the devices the role of tunnel barrier imperfections inside a magnetic tunnel junction is basically unknown. Furthermore, the influence of Oersted field effects on magnetic switching processes is still an open question. To exclude any interfacial imperfections, leakage channels or intermixings, one could think of a magnetic tunnel junction where the magnetic electrodes are separated by vacuum. However, this kind of magnetic tunnel junctions has not yet been realized for experiments using high spin-polarized currents. Consequently, it remains an open question if current-induced magnetization switching across a vacuum barrier is possible.

Spin-polarized scanning tunneling microscopy (SP-STM) opens the perspective for a new class of experiments that provide a deeper insight into the microscopic processes due to spin torque effects. SP-STM is a powerful tool to image the magnetic structure of surfaces at a lateral resolution down to the atomic scale [19, 20]. Here, a magnetic tip approaches a magnetic sample. When a bias voltage is applied to the electrodes, a spin-polarized tunnel current starts to flow between tip and sample at small distances. In this configuration the spin-polarized tunnel conductance between a magnetic tip and a magnetic sample is measured to determine the magnetic state of the sample. Besides, SP-STM realizes the model of a "perfect" magnetic tunnel junction, with vacuum serving as the barrier separating the two magnetic electrodes, namely the tip and the sample. Since the tunnel current exponentially depends on the distance between tip and sample, the same tip that determines the magnetic state at low current may be used for the manipulation of magnetism when tunneling at decreased distance, acting as a source of high spin-polarized currents. The torque exerted by the electrons switches the magnetization in a direction to align it parallel to the spin-polarization of the current. However, whereas SP-STM already provides established reading capabilities at ultimate resolution, it has not yet been shown experimentally that SP-STM may also be used for applications to manipulate magnetism at that scale.

Using devices that provide reading *and* writing capabilities at ultimate lateral resolution could lead to a further increase of data density in storage media. However, with decreasing particle size the so-called superparamagnetic limit will be reached in the near future. For particles having a size less than a critical size, thermally induced magnetization reversal processes can occur that destroy the information stored in the particle [21]. In theoretical elaborations by Néel [22] and Brown [23] the switching rate has been determined under the assumption of the magnetization being coherent at any time—even during the switching process. In this model the switching rate is exponentially dependent on the temperature and the size of the particle. A detailed understanding of the microscopic processes involved in the switching behavior could help to engineer materials that exhibit a stable magnetization at small sizes and therefore may enable the realization of new types of ultra-high data density storage devices.

Due to the limited lateral sensitivity, most of the experiments in the past have been performed on ensembles of assumedly identical objects, and not on a single particle. Consequently, effects that are related to the shape or the size of individual particles are not detectable in the averaged signal. Only recently the switching behavior of individual nanoparticles has been investigated experimentally [24–27]. It has been shown that for compact particles the Néel-Brown theory applies very well, while for particles with a distinct elongation a transition from a coherent rotation of all magnetic moments to the nucleation and propagation of a domain wall occurs.

For the experiments that have been performed within this work, ferromagnetic nanoislands with uniaxial anisotropy and consisting of about 100 atoms on a W(110) substrate were prepared that switch their magnetization due to thermal activation. To get a deeper understanding of the switching processes involved in magnetization reversal, the switching behavior of the nanoislands as a function of temperature and size has been investigated systematically. After that, the possibility of current-induced magnetization switching using SP-STM has been tested. Before trying to reverse the magnetization of stable nanoislands, experiments on the current-induced magnetization switching have been performed using a sample system of thermally switching nanoislands. In contrast to a stable magnetic particle, where a minimum threshold current would have to be applied to excite a magnetic reversal, even small spin torque effects should already significantly influence the switching behavior of nanoislands that reverse their magnetization due to thermal activation, and these effects should lead to a modification of the state-dependent mean lifetime between two switching events. Furthermore, the high spatial resolution of current-induced magnetization switching with SP-STM could provide new insight into the details of the processes involved in the magnetization reversal that are inaccessible in experiments with buried interfaces.

In this thesis the switching behavior of magnetic nanoparticles and the question whether SP-STM could also serve as a tool to manipulate the magnetism of nanostructures at the atomic scale are investigated. After introducing the theory of current-induced magnetization switching in Ch. 2, the working principles of STM and SP-STM are covered in Ch. 3, followed by the experimental setup and the preparation of tips and samples in Ch. 4. The results of the investigations of thermally switching magnetic nanoislands are presented in Ch. 5, whereas the results of the experiments regarding the current-induced magnetization switching with SP-STM using are presented in Ch. 6 for the system of thermally switching nanoislands and in Ch. 7 for quasistable nanoislands. Finally, a summary and outlook are given in Ch. 8.