Chapter 1

Introduction

Most of us store data on a hard disk in a computer. During my travels I like to take photos and store my precious experiences in digital form. However, to transfer it to a hard disk in my laptop and to retrieve it, takes time. I am writing my dissertation using LaTeX. To scroll pages in PostScript format is not so fast, at least for pages that contain some pictures (especially the magnetic domain structure images you will see later on). Furthermore, if one wants to have high-resolution pictures, it may take even more time.

Nowadays, data storage devices contain magnetic trilayered systems, so called spin valves (SV) [1] or magnetic tunnel junctions (MTJ) [2,3], in which two ferromagnetic (FM) layers are separated by a non-magnetic (NM) spacer layer. The response time of these devices is in the nanosecond (ns) range. The SV systems are used in read heads of hard disk drives (a scheme is shown in the inset of Fig. 1.1), which consist of two FM layers (light grey), a NM conducting layer (middle grey) and an antiferromagnetic (AFM) layer (dark grey). The AFM layer serves to pin the magnetization of one of the two FM layers. The magnetization direction of the unpinned soft magnetic layer can be changed by the stray field from the media (the disk), while the magnetization direction in the pinned hard layer stays fixed. The output of these devices is a signal by the giant magnetoresistance (GMR) effect: a difference in magnetization angle between the two FM layers gives rise to a difference of electrical resistance [4, 5]. The waiting time mentioned above is directly related to how fast the magnetization in the soft FM layer in the read head can switch.

Magnetic random access memories (MRAM) are new data storage devices. Bit and word lines are crossing perpendicularly connected by small magnetic multilayers that can be used for data storage (Fig. 1.2). MTJ system will be used there, which is similar to SV, but instead of a metallic spacer a thin insulating spacer layer is used. A combination of magnetic fields from electrical current though the bit and word lines is able to flip the magnetization in the soft layer of one particular cell. In contrast to silicon-based RAM, this is a non-volatile data storage device, so even after switching off the main power, the data is still there. A part of this thesis is dedicated to the

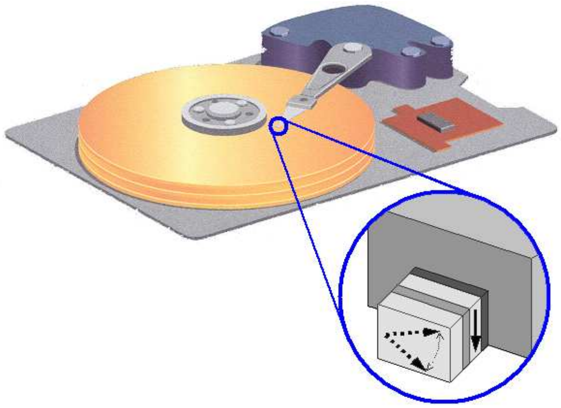

Figure 1.1: Picture of a hard disk drive. The tip of the read head is enlarged, and the SV device is visible. The SV device is composed of two FM layers (light grey), a NM spacer layer (middle grey) and an AFM layer (dark grey). One of the FM layers is magnetically pinned by the AFM layer. The magnetization direction of the other FM layer can be changed by the stray field from the disk (dotted arrows). The difference in the relative orientation between the magnetization directions of the two FM layers causes a magnetoresistance effect.

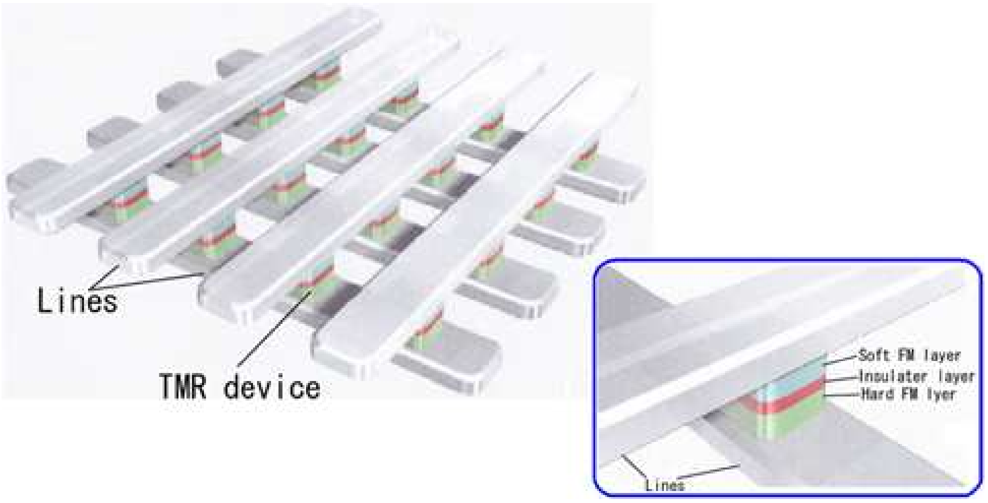

Figure 1.2: Picture of MRAM. White lines crossing perpendicularly are the bit and word lines. At the crossing points, there are MTJ systems for data storage, which consist of a soft and a hard magnetic layers (light grey) separated by an insulating layer (dark grey).

study of the fast switching of the soft magnetic layer in MTJ like trilayer systems.

The magnetization reversal mechanism has been widely investigated for single magnetic films as followings. The relation between the propagation speed of a magnetic domain wall and the amplitude of the external field in magnetic films has been studied since a long time. The linear dependence of the wall velocity on the amplitude of the field has been empirically suggested by

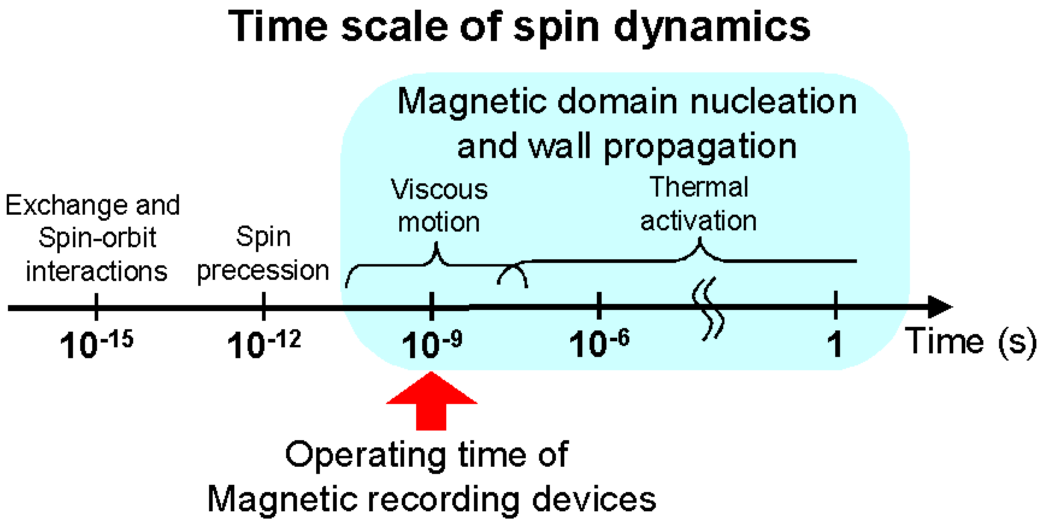

Figure 1.3: Time scale of spin dynamics.

Sixtus and Tonks in 1931 [6]. More recently in 1956, Rodbell and Bean [7] observed different modes of the wall motion in high field and low field ranges, and showed that each case has its coercivity and mobility. For the domain wall motion in low fields, a pinning barrier for the wall motion has to be included in the coercivity. The wall motion is hindered or blocked by intrinsic defects in a material or on a surface. In that case, the domain progresses step-by-step from one boundary (defect) to another, the so called Barkhausen jumps. Later on, it has been suggested that the wall velocity increases exponentially with field [8–10]. In the case of magnetic thin films, this jump-like wall motion related to the size of surface terraces has been observed using Kerr microscopy [11]. This type of wall motion is a thermally activated process, and the domain wall velocity is small, in the range of m/s or even slower. The time scales of spin dynamics related to the magnetization reversal are showed in Fig. 1.3.

The linear behavior of the wall motion in the higher field regime, the so called viscous motion, could be explained using the Landau-Lifshitz (LL) equation [12, 13] for a one-dimensional Bloch wall moving in a direction perpendicular to the wall plane, which is in the ns range (see Fig. 1.3). LL equation can describe well the precessional motion of free spins, which is in the picosecond range.

In the femtosecond range, exchange and spin-orbit interactions take place. Here, the LL equation fails, and quantum mechanical effects have to be taken into account [14, 15].

Up to now, the magnetization reversal dynamics in magnetic multilayered systems have not been studied by magnetic domain imaging method with element selectivity. Because of experimental complexities. However, I have successfully performed such experiments by a novel combination of x-ray magnetic circular dichroism, photoelectron emission microscopy and a stroboscopic pump-probe technique. The time-resolution was sub-ns range, which is necessary to study the magnetization reversal dynamics in the devices mentioned above, since they are operating in the GHz range. The magnetization reversal mechanism in soft magnetic layers in such magnetic multilayered devices has not well studied and has not well understood, because of being complicated micromagnetic effects, like surface/interface roughness, magnetic coupling, anisotropy energy, wall energy, spin structure inside domain walls, and stray field from a magnetic domain wall. A better understanding of the reversal mechanism in (magnetically coupled) trilayer systems may help to improve the magnetization reversal speed.

The magnetization reversal dynamics in the ns range for soft layers of magnetic multilayered systems, SV and MTJ like trilayers, was studied by both single-pulse experiments and pump-probe experiments. I found that the magnetic coupling between two ferromagnetic layers induced by modulated interface roughness promoted or hindered domain wall motion [16]. An induced uniaxial anisotropy energy lowered the reproducibility of wall motion [17]. I also observed the influence of the domain wall energy on the wall motion. When two walls are near by, they prefer to combine to reduce the total wall energy. An increase of domain wall speed has been observed when two domains were merging [18]. This behavior resembles two water droplets merging. However, in the case of isolated domains, the domain wall energy acted against expansion of domains by the Zeeman energy [19]. The observed domain wall propagation speed increased upon increasing the external field, from 300 m/s up to 2000 m/s, then saturated for even higher fields. This was due to the breaking of the spin structure inside the wall [20–22]. When domain walls presented in a hard magnetic Co layer, the stray field of these domain walls initiated magnetic domain nucleation in the FeNi layer just above [23]. All these observations were performed using a novel combination of x-ray magnetic circular dichroism, photoelectron emission microscopy, and pump-probe/single-pulse technique, which allowed imaging the dynamics of magnetization reversal with element selectivity (for the first time). A few hundred nm lateral resolution and sub-ns time resolution were achieved.

I report also the reduction of magnetic domain size by a competition of magnetic energy terms, magnetostatic, exchange, anisotropy and Zeeman energies, in static condition on an epitaxially grown Co/Ni double layer on a Cu(001) surface. A slow magnetization reversal dynamics in the timescale of seconds by nucleation of domains and by jump-like wall motions have been observed upon increasing the substrate temperature or upon variations of the anisotropy energy as a function of thickness during Co deposition. These magnetization reversal mechanism could be understood by considering static magnetic terms, a distortion of crystallographic structure and spin fluctuations.