Chapter 7

Conclusion

Magnetization reversal in the timescale of seconds has been studied in epitaxially grown Ni films on Cu(001), where the Ni film had an out-of-plane anisotropy energy, by increasing the substrate temperature from room temperature to the Curie temperature ($\sim$435 K). Growing a wedge-shaped Co layer on top of this sample, an SRT from out-of-plane to in-plane magnetization has been observed with increasing Co thickness. A lateral motion of the SRT line is observed upon growing more Co material.

- In the out-of-plane region close to the SRT, stripe shaped magnetic domains are formed by a competition of magnetic energies. The stripe period was decreasing when approaching the SRT.

  A lateral motion of the SRT line has been observed upon increasing the thickness of the wedge-Co layer, the SRT moved to stay at constant Co thickness. This motion is governed by a creeping wall motion of the stripe domains and shrinking of the width.

- In the region with pure out-of-plane anisotropy of the same sample, i.e., without Co overlayer, a reduction of domain size and nucleation of new domains were observed upon increasing the substrate temperature. The thermal energy lowered the anisotropy energy by a distortion of the crystal structure, thus the wall energy is reduced as well, leading to a reduction of domain size. Just before reaching the Curie temperature from below, a splitting of the stripe domains and domain nucleation took place due to spin fluctuation effects.

I conclude from the above observations that the slow magnetization reversal dynamics (magnetic domain nucleation and jump-like wall motion), driven with no external field, is related to the intrinsic magnetic properties, (magnetostatic, exchange, anisotropy, Zeeman energies) and to a distortion of the crystallographic structure and spin fluctuations by a thermal energy.

The element selective magnetic domain imaging with the ns-temporal resolution, which is a combination of XMCD, PEEM and pump-probe/single-pulse technique, has been performed to clear the mechanism of magnetization reversal in a magnetically free layer of SV or MTJ trilayers. The following main results have been obtained:

- It was observed that the coupling energy between two ferromagnetic layers played an important role for the magnetization reversal in the FeNi layer of the SV like trilayer system. When the magnetization of the FeNi layer reversed into the direction of the Co magnetization, domain wall propagation was the predominant mechanism. On the contrary, when it reversed against the direction of the Co magnetization, domain nucleation mainly took place. This is explained by local magnetic coupling at step-bunches, which either promotes or hinders the wall motion in the former or the latter case, respectively.

- The influence of the magnetic anisotropy on the magnetization reversal has been observed. In the SV sample with uniaxial anisotropy in the film plane, the domain walls were basically parallel to that direction. However, in the SV sample with almost negligible anisotropy energy in the film plane, the direction of domain walls was random, and the size of domains was much smaller (a few μm range). The magnetization reversal mechanism, mainly by domain wall propagation, was microscopically reproduced for successive field pulses for the latter and not reproduced for the former. If the sample has a negligible anisotropy energy, the domain walls have a smaller stiffness and pinning centers have a larger influence on the reversal. They distort the direction of domain walls and hinder the domain wall motion, which causes the high reproducibility of the wall motion.

- For the 4 nm-thick FeNi layer in the MTJ like trilayer system, the experimentally observed velocity of the wall motion along the easy axis of magnetization was above 300 m/s, and saturated at around 2000 m/s, in which case the effective field was 5.2 mT. The obtained mobility was 1600 m/(s mT). The saturation field, the so called Walker limit field, is in good agreement with the estimated value of 5 mT, obtained from $1/2\mu_0\alpha M_S$, where M_S is the saturation magnetization and α the damping constant (= 0.01).

- The SV sample with a negligible anisotropy energy in the film plane had micron-sized domains. In a time-resolved experiment, a faster motion of domain walls was observed if two domains were merging. This was qualitatively understood by taking into account the domain wall energy. It becomes important for smaller domains. A domain wall motion which reduces the total wall energy by merging of two existing domains is thus much faster than an expansion of domains.

- The domain wall energy is decisive for the wall motion has been seen also in another experiment. Here during magnetic field pulses, magnetic domains were nucleated and subsequently expanded with time. However, there was an apparent delay in the domain expansion that depended on the amplitude of the field pulses. This behavior was fully understood by taking into account the domain wall energy. The gain in the Zeeman energy tries to expand the nucleated domains, but the domain wall energy, which is relatively large when domains are small, tries to hinder this expansion.

- The nucleation field in the FeNi layer of the MTJ like trilayer was drastically reduced by the stray field from the domain wall in the Co layer. Micromagnetic simulations showed that this stray field locally tilts the magnetization in the FeNi layer to almost the hard axis of magnetization. In that region, the torque acting on the FeNi magnetization by the field pulse is higher, so that reversed domains are more easily nucleated.

In conclusion, for a fast magnetization reversal in magnetic multilayered systems, a high density of domain nucleation centers may not be preferable, which can be induced by surface/interface roughness and by a weak magnetic anisotropy. The former generates local coupling fields which act as energy barriers for domain wall motion, and the latter creates 360° domain walls by the interaction between walls, which are hard to be removed. Furthermore, the speed of domain wall propagation was reduced after the nucleation of the domains. The wall energy which acts against the domain expansion is relatively large when domains are small.

The reduction of the nucleation field in a free layer was systematically achieved by inducing a domain wall in the pinned layer. A smaller switching field, for example for a magnetic hard disk read head, allows to reduce the amplitude of the stray field from magnetic cells on a hard disk, leading to a reduction of the size of magnetic bits.

The above mentioned micromagnetic effects acting in SV or MTJ like systems could be successfully observed owing to the suitability of XMCD-PEEM experiments with pump-probe/single-pulse technique.