Dissertation

High Frequency Behaviour of Magnetic Thin Film Elements for Microelectronics

Chumakov Dmytro

Tag der Einreichung: 20.02.2006
Table of contents

Introduction 1

1. Theoretical background and overview of recent research activities on magnetization dynamics 3

1.1 Brief overview of ferromagnetism 3

1.2 Elements of modern domain theory 4

  Exchange stiffness energy 4

  Anisotropy energy 5

  Magnetic field energy 6

  General micromagnetic equation 6

1.3 Magnetization processes in soft magnetic thin film elements 7

1.4 Magnetization dynamics 8

  Landau-Lifshitz equation 8

  Macrospin model 9

  Micromagnetic calculations 10

  Time resolved microscopy studies of magnetization dynamics—recent progress 11

Brief summary and objective outline 13

2. Experimental 15

2.1 Basics of the common Kerr microscopy 15

  Magneto-optical Kerr effect 15

  Kerr microscope 17

  Background subtraction and contrast enhancement 17

2.2 Time resolved Kerr microscopy 19

  Stroboscopic imaging 19
Time resolved ICCD camera

Setup of the time-resolved microscope

Time resolution of the experiment

2.3 Samples for dynamic magnetic studies on shaped elements

Strip-line-based samples

Calculation of field strength

Remarks about fields and waves in the stripline

Conclusions

3. Dependence of the switching behaviour on the geometry of field application and the shape of the elements.

3.1 Square shaped element in fields applied along the diagonal direction

Quasistatic switching

Dynamic switching

3.2 Square shaped element in fields applied along the vertical edge

Quasistatic switching

Dynamic switching

3.3 Rectangular 40 µm x 28 µm element

Quasistatic switching

Dynamic switching

3.4 Rectangular 40 µm x10 µm element

Quasistatic switching

Dynamic switching

3.5 Discussion on switching peculiarities in differently applied fields and differently shaped elements

Conclusions
4. **High frequency behaviour of micro inductor**

4.1 Purposes and objectives of the study. Sample description

4.2 Inductor in slowly changing magnetic fields

   Field applied parallel to the easy axis

   Field applied perpendicular to the easy axis

4.3 Inductor in pulsed magnetic field

   Experiment details

   Dynamic behaviour of the elements

   Summary on inductor’s dynamic behaviour in pulsed field

4.4 Microscopic studies under harmonic excitation

   Experimental details

   Elements under 50 MHz excitation

   Elements under 100 MHz excitation

   Elements at 200 MHz excitation

   Elements at 500 MHz excitation

   Summary on the inductor’s magnetic behaviour

5. **Conclusions**

6. **References**
Introduction

Throughout the history of technology development magnetism has been playing a critical role in many application areas. Initially magnetic phenomena have become a cornerstone in the functionality of large-scale magnetic devices, such as power generators, transformers and electric motors. The first applications of magnetic materials have triggered an immense interest in the research of magnetic phenomena and material properties related to these phenomena. With increasing progress in the field of electronics an application field for magnetism has been proportionally increasing, which in turn has also increased the amount of further magnetic research.

The development of electronics has been always pursuing the purpose of miniaturization. This first of all is necessary for achieving high integration rates of electronic circuits, but there is also another critical aspect of miniaturization, which is related to the functioning speed of a device. For the implementation of electronic devices in high speed circuits these devices must be made much smaller than the wavelength of the processes taking place in the circuit. Thus magnetic devices and applications had to follow the same path of reducing linear size and increasing functioning speed. Nowadays magnetic materials are used in virtually every electronic device in form of inductors, magnetic field sensors and similar applications. But the most outstanding field for magnetic materials is data storage. This is also a most challenging field, because storage systems must be fast enough to be relevant for modern standards of data transfer rates and at the same time they have to be small enough to be compatible with modern data density standards. Up to now computer hard drives constitute the main application field for magnetic materials in the data storage domain. Another upcoming challenge are Magnetic Random Access Memories (MRAMs). These are devices based on utilization of the Giant Magnetoresistance (GMR) or the Tunneling Magnetoresistance (TMR) effect on complicated structured multilayer thin film elements. The most exciting feature of MRAMs is their non-volatility, which means that the information stored in it will not be lost when the power is turned off. Generally speaking, MRAMs promise to hopefully replace not only existing non-volatile FLASH memories but also all RAMs [IBM ]. The ultimate criteria for the relevance of MRAM technology is it’s compatibility with modern demands on data transfer rates, which in turn depend directly on the switching speed of magnetic elements used in them. This is why studying of the dynamic behavior of structured thin film elements becomes an issue of critical importance for successful control of their switching and thus for
successful engineering of novel promising devices such as magnetic memories. Nowadays a lot of research activities in the field of magnetization dynamics pivot on the point of modern data storage and memory applications.

In context of increasing practical interest towards thin-film magnetic devices, such as MRAMs, microinductors, etc., the main emphasis in the working group for Magnetic Microstructures at IFW-Dresden is laid on wide-field Kerr microscopy studies of magnetization processes. This is one of the established and most powerful methods for analyzing the microscopic magnetic behavior of materials. A huge amount of peculiarities of quasistatic magnetization processes was discovered using this method [Hub98]. Stimulated by growing interest in dynamic magnetization processes, an experiment, based on a conventional Kerr microscope, was built up, allowing to effectively study magnetization dynamics in patterned magnetic samples and devices on the nanosecond timescale. The approach is named “Time-resolved wide field Kerr microscopy”. This thesis introduces this new imaging approach and presents various experimental results obtained. It compares dynamic and quasistatic processes, and points out some very important similarities and differences between them. The influence of the element’s form on its dynamic switching is studied and discussed. The thesis also touches the influence of induced anisotropy on the dynamic behavior of micro inductive coils, based on amorphous materials. Some of the results obtained and some considerations might become of practical interest and importance for the engineering of dynamic magnetic devices.
1. Theoretical background and overview of recent research activities on magnetization dynamics

This chapter first briefly summarizes the most essential theoretical considerations about the nature of ferromagnetism and magnetization processes. After this the peculiarities of dynamic magnetization reversal are discussed, and some important differences to quasistatic switching are mentioned. The chapter closes with a short overview of results of modern experimental and theoretic research on dynamic switching. It also gives an outlook, which summarizes the challenges, assaulted in this work, that should give a further contribution to today’s existing knowledge on fast magnetic switching processes.

1.1 Brief overview of ferromagnetism

A fundamental property of ferromagnetic materials is the presence of regions with spontaneous magnetization. These magnetized regions are called magnetic domains. The magnetization inside a certain domain is homogeneous, i.e. all magnetic moments inside that region point in the same direction. Figure 1.1 shows examples of magnetic domains in different materials. The first and most important steps in understanding why ferromagnets break up into domains were made by Weiss [Wei07], Frenkel [Fre30], Bloch [Blo32] and Heisenberg [Hei31]. The scientists at that time came to the understanding, that breaking up into domains would minimize the magnetostatic energy of the material. These considerations were confirmed by experiments of Bitter in 1932 [Bit32], where he used metallic powder to visualize the stray field of domains. Another breakthrough in understanding of magnetic domains was done by Landau and Lifshitz in 1935 [Lan35]. They have theoretically derived a stray field free domain model (Fig. 1.2) and proven this domain state to be a minimum energy state. The feature of such domain structure is that the magnetization forms a closed loop, avoiding field leakage, and thus achieving a considerable energy reduction. Important

Fig. 1.1 Examples of magnetic domains. (a) Landau flux-closure domains in thin film permalloy element. (b) Maze domains in perpendicular garnet film. (c) Branched domains in cobalt crystal. Images (b) and (c) are copied from [Hub98].
conclusions and consequences of this model are comprehensively summarized by Hubert and Schäfer [Hub98, p.7]. The simplified consideration turned out to be perfectly true for uncomplicated, anisotropy free soft magnetic samples [Fig. 1.1 (a)]. But a lot of macro- and microstructural features like stress, crystalline cubic or induced anisotropies, the defects of microstructure, and many other factors, which play an important role in determining complicated domain patterns in every specific case, were left out in this treatment. This is why more complicated domains, for example as shown in Fig. 1.1 (b) and (c), cannot be explained by this model only. Later a great amount of further studies and research have been performed, which enormously expanded and refined the initial considerations about domains.

1.2 Elements of modern domain theory

As any other physical system a magnetized body strives to achieve the state of minimum possible energy. There are six major energies, which play a critical role in magnetization processes: exchange energy, anisotropy energy, external field energy, stray field energy, external stress energy, and magnetostrictive self-energy. After summing up these contributions and integrating over the whole volume of the body, an integral expression for the total magnetic energy is obtained [Hub98, p.148].

Exchange stiffness energy

The exchange energy is described by the interaction between two spins $S_1$ and $S_2$, as derived by Heisenberg,

$$E_{ex} = -2J_{ex} S_1 \cdot S_2 = -2J_{ex} S_1 S_2 \cos \varphi$$

where $J_{ex}$ is the exchange integral and $\varphi$ is the angle between the interacting spins. This energy reaches its minimum when the spins have a parallel alignment. A misalignment of spins will cause an increase in exchange energy and thus introduce an effective stiffness. This issue was systematically reconsidered by Landau and 

Fig. 1.2 Flux-closure states, suggested by Landau and Lifshitz. Magnetic domains are oriented so, that flux remains trapped inside the body. This minimizes the stray field energy of a given ferromagnet.
Lifshitz. They have derived today’s basic form for the exchange energy density term:

\[ e_{ex} = A (\text{grad} \cdot \mathbf{m})^2 \] (1.1)

where \( A \) is an exchange stiffness constant, and \( \mathbf{m} \) is the local magnetization vector, expressed in reduced units:

\[ m = \frac{M}{M_s} \]

\[ A = \frac{2J_{ex}S^2}{a} \] for BCC structure, and \( A = \frac{4J_{ex}S^2}{a} \) for FCC structure [Cul72]

\( M \) is the local magnetization vector, \( a \) is the lattice constant, and \( M_s \) the saturation magnetization.

**Anisotropy energy**

The anisotropy energy is basically caused by spin-orbit interactions. Being strongly fixed to the lattice, the orbital moments interact with the spins of the electrons and thus impose a preferred orientation direction on the body’s magnetization. This results in an energy increase, if magnetic moments deviate from the easy direction. For cubic materials the expression for the anisotropy energy is:

\[ e_{kc} = K_{c1} (m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2) + K_{c2} m_1^2 m_2^2 m_3^2 \] (1.2)

where \( K_{c1} \) are the cubic anisotropy constants. Normally only \( K_{c1} \) are taken into account, and all high order terms are neglected. In polar coordinates the integrand assumes the form:

\[ e_{kc} = (K_{c1} + K_{c2} \sin^2 \Phi) \cos^4 \Phi \sin^2 \Phi \cos^2 \Theta + K_{c1} \sin^2 \Phi \cos^2 \Theta \] . (1.2a)

For the case of hexagonal and tetragonal structures the body has just one easy axis, and the corresponding anisotropy is therefore called uniaxial. The expression for uniaxial anisotropy in polar coordinates is:

\[ e_{ku} = K_{u1} \sin^2 \Phi + K_{u2} \sin^4 \Phi \] . (1.2b)

There is another important anisotropy type to consider, especially in amorphous or nanocrystalline materials, which is induced anisotropy. This anisotropy appears due to magnetization during the annealing or film
growth. In polycrystalline or amorphous materials the induced anisotropy reduces to uniaxial anisotropy whose axis coincides with the magnetization vector direction. If the sample is homogeneously magnetized during growth or annealing (usually achieved by an application of the external field), the induced anisotropy is well defined and homogeneous. Some of our samples have been grown without an external field application. They possess weak randomly oriented anisotropies, which do not produce a strong influence on the magnetization processes.

**Magnetic field energy**

A further energetic contribution comes from magnetic field. An effective magnetic field, acting on a given body, generally consists of two parts: externally applied field and self-induced field of the magnetized body. The energy, imposed by the external field $H_{\text{ext}}$ is:

$$E_{\text{ext}} = - \int (H_{\text{ext}} \cdot M) dV . \quad (1.3)$$

In case of a homogeneous external field this energy does not depend on peculiarities of the domain pattern in the sample. Only the mean value of magnetization matters in this case. The contribution of the self-induced field to the total energy is the most complicated part of domain theory. The energies discussed above are basically dependent on the value of magnetization at a given location only. For the demagnetizing energy this is not the case anymore. To calculate this energy at a given point not only the local magnetization value, but also the magnetization distribution all across the sample must be considered. The general mathematic description of the demagnetizing field energy assumes the form:

$$E_d = - \frac{1}{2} \int (H_d \cdot M) dV . \quad (1.4)$$

where $H_d$ is the demagnetizing field. This field opposes the magnetization, which creates it. Hence the integral has always a positive value and thus any magnetized body always has to pay the energetic price of $E_d$.

**General micromagnetic equation**

Summarizing the obtained energies yields the following expression for the total energy:
\[ E = \int \left( A(\nabla \cdot m)^2 + e_{\text{anisotropy}} - \mathbf{H}_{\text{ext}} \cdot \mathbf{M} + \frac{1}{2} \mathbf{H}_d \cdot \mathbf{M} \right) dV . \quad (1.5) \]

This is a general form of micromagnetic equation. There are other factors, which may as well contribute to the total energy of a magnetized body, like exchange anisotropy (effective fields induced by exchange interactions), magnetostrictive self-energy, and energies due to magnetoelastic interactions with the stress fields. But these are not relevant in the context of this work. By applying the methods of variational calculus, the conditions under which the integral in equ. (1.5) assumes its minimum value can be found, and thus the optimal magnetization distribution in a sample can be calculated. This is usually done by application of numerical methods, because writing of explicit analytic expressions for terms like equ. (1.4) is a too complicated task. Explicit equations may be written for elliptical bodies only. There are though some approximations which allow to estimate the energy of a demagnetizing field, for instance for the case of rectangularly shaped prisms [Aha98]. But for a general case the problem of the demagnetizing field remains analytically unsolved.

1.3 Magnetization processes in soft magnetic thin film elements

In a patterned thin film sample with very low anisotropy magnetization processes are dominated by exchange, external field, and demagnetizing field terms. It is known, that the geometry plays a dominant role in determining a particular domain pattern for a given sample [Ber86]. Let us assume a sample that is uniformly magnetized by an external field. This state minimizes the contribution of exchange stiffness [equ. (1.1)] and magnetic field [equ. (1.3)] terms to the total energy, but strongly maximizes the contribution of the demagnetizing field term [equ. (1.4)]. As long as the applied field is strong enough, the term (1.3) is dominant. After reducing the field below some critical value the influence of demagnetization, determined by equ. (1.4), will trigger the reversal process in the sample. Magnetic domains will start to nucleate in the sample and then grow to ultimately adjust their size and shape in such way, that the magnetic energy is minimized. The peculiarities of this process and the appearance of magnetic domains are determined by a complicated balance between the three listed energy contributions. Elements, for which the above considerations are true, are treated in chapter 3. These elements possess negligibly weak induced anisotropies, which practically produce no influence on the reversal processes. These anisotropies appear due to parasitic effects during film deposition and patterning. They are usually distributed over elements’
area, and do not possess an overall preferred direction. The reversal behaviour of such elements is mainly determined by their shape. The effects due to magnetoelastic interactions are expected to be negligibly small because the used permalloy has a nearly zero magnetostriction constant. Chapter 4 deals with inductive devices, which have a considerable induced anisotropy. As mentioned before, the induced anisotropy mathematically assumes the form of a uniaxial anisotropy, thus also the term (1.2b) plays a role during the reversal. The uniaxial anisotropy is equivalent to introducing an additional effective field, which tends to magnetize a sample in a certain direction. It will be shown that this field mainly determines the remanent state of the element in the quasistatic case and introduces an interesting zest to the dynamic behaviour of the sample.

1.4 Magnetization dynamics

In discussion above it has been assumed that the magnetization is simply searching a way to reduce the total energy of the body and reach its stable state. This is basically achieved by building and reordering of magnetic domains. But the duration of this process on the time scale has not been considered, and thus the process has implicitly been assumed to be quasistatic, where magnetic moments simply rotate in the most favourable direction, and only their certain established equilibrium states are considered. This chapter describes the differences between dynamic and quasistatic behaviour, introduces the most essential aspects of magnetization dynamics theory and provides a brief survey of experimental and theoretical results of other groups working in this area.

Landau-Lifshitz equation

To describe the behaviour of the magnetization on the nanosecond timescale a more complicated approach is needed. The cornerstone of modern knowledge about dynamics is the Landau-Lifshitz equation:

$$\frac{1}{\gamma} \frac{dM}{dt} = -[M \times H] - \frac{\lambda}{\gamma M_s} (M \times [M \times H]).$$  (1.6)

Parameters $\lambda$ and $\gamma$ are the Landau-Lifshitz damping constant and the splitting factors, respectively, $M_s$ is the saturation magnetization, and $H$ is a total effective field, acting on the magnetic moment. This field includes the external field, demagnetizing fields and effective anisotropy fields. This equation was postulated
in the same work [Lan35], where stiffness energy and closure domains were first introduced. It phenomenologically describes the motion of magnetic moments in magnetic fields. The magnetic moments do not immediately rotate in the direction of the effective field, as assumed before. They rather perform a more complicated motion as shown in Fig. 1.3. The first term of equation (1.6) describes the orbital motion of the magnetic moment around the field axis, also called precession. The second term introduces damping to this motion. The damping gradually reduces the radius of the precession orbit, finally aligning the magnetic moment towards the field direction. Equation (1.6) may be re-written in the following form:

\[
\frac{dM}{dt} = -\gamma [M \times H] + \frac{\alpha}{M_s} [M \times \frac{dM}{dt}] . \quad (1.7)
\]

This equation is known as Landau-Lifshitz-Gilbert equation, with the Gilbert damping constant \( \alpha \). Miltat et al. [Mil02] provide a «more tractable » form of the LLG equation, rewriting it as :

\[
(1 + \alpha^2) \frac{dM}{dt} = -\gamma [M \times H] - \frac{\alpha \gamma}{M_s} [M \times [M \times H]] . \quad (1.8)
\]

Virtually every modern micromagnetic calculation of the dynamic behaviour of a sample or device uses one of the forms of the LLG equation.

**Macrospin model**

The simplest approach to get a notion for the switching behaviour of a given particle is to apply a macrospin approximation. The magnetic moments are assumed to rotate simultaneously and coherently everywhere across the sample, as if they were just a single spin. This of course eliminates the possibility to take magnetic domains and domain boundaries into account. Although extremely simplified, this model is widely used to estimate some basic features of the switching behaviour, like switching speed, the role of damping in
switching, determining optimal values for pulse amplitude and length. In the literature this approach is used for examining the conditions for so-called ballistic trajectory switching. In case of ballistic switching, the magnetization in the element makes one complete 180° turn and immediately finds its equilibrium state without further motion, as illustrated in Fig. 1.4 (a). In case of non-ballistic switching the macrospin makes a flip close to 180° and then slowly oscillates down to its equilibrium position [Fig. 1.4 (b)]. This slow relaxation is also called “ringing”. The problem of ballistic switching is an issue of critical importance for data storage applications.

Good generalized results on this subject are presented by Bauer et. al [Bau00i]. An application of a field pulse perpendicular to the magnetization direction may also cause the 180° switching, known as precessional switching, emphasizing that it is not the field reversal, but the magnetization precession that causes the switching [Bau00ii]. Another switching mechanism of technical and research interest is the current-induced switching. In this case the magnetization reversal is forced by the spin-polarized current [Slo96]. This case also involves a complicated oscillatory behaviour of spins, and the theory is based on a modified and extended Landau-Lifshitz equation.

**Micromagnetic Calculations**

The most complicated, but also the most informative way to theoretically approach a problem of dynamic switching is to perform dynamic micromagnetic calculations. For this reason a general micromagnetic equation is solved together with the LLG equation (1.5), (1.6) or (1.7). The issue of solution complexity is specially addressed on the Web-Page of the National Institute of Standards and Technology [NIST].

![Fig. 1.4 (a) Ballistic switching of a macrospin. After the field application the magnetization reaches its new equilibrium state in just one flip. (b) Non ballistic switching. The magnetization rapidly turns to the vicinity of the new equilibrium, but the final state is reached only after a long ringing (from [Hil02]).](image)

**Fig. 1.5** The average y-magnetization component shown as a function of time during dynamic reversal of a 500 nm x 125 nm x 3 nm Permalloy prism. Copied from NIST Web-page.
Here a so-called standard problem for micromagnetic solution methods is offered, where the reversal process of a 500 nm x 125 nm x 3 nm Permalloy prism has to be calculated for an immediately applied pulse field. The results are then thoroughly compared and discussed. Figure 1.5 shows calculation results from different groups. Here the net y-component of the magnetization is calculated as a function of time, and its complicated oscillatory behaviour is seen. Another set of calculations of magnetization processes in confined structures was done by Hertel [Her04]. Here a switching of a square element whose edge length is 100 times the thickness and the thickness itself equals the exchange length is studied. The field pulse is applied to an element with initial Landau state, and domain wall and vortex motion are calculated. The results are presented in Fig. 1.6, showing that the motion of the vortex is much slower than that of the domain walls. Approximately 400 ps after the pulse application the domains almost completely disappeared from the element, whereas the vortex was still present and was pulled out from the element only some 500 ps later. These calculations were performed for a high damping parameter $\alpha$ of 0.5. Such structures, as shown in Fig. 1.6, cannot be quasistatically observed on simple Permalloy films. In the same article the distribution of magnetization waves in elements with low damping is calculated. There are other calculations by Guslinko et. al. [Gus02], which predict a circular motion of the vortex with certain resonance frequencies. Guslienko’s calculations have recently found an experimental confirmation [Cho04]. The micromagnetic modelling offers a very deep insight into the reversal behaviour of a sample, and also enables scientists and engineers to be able to effectively apply and further develop the new knowledge. But in the ideal case a calculation has to first find its experimental validation to confirm and certify its predictive power. The most useful tool for experimental studies of magnetization dynamics are approaches based on time resolved magnetic microscopy.

**Time resolved microscopy studies of magnetization dynamics-recent progress**

Actually the issue of switching speed of a structured element in context of data storage applications was
already addressed in 1963 [Con63]. Thinking about the claims on the data rates of computers back in 1963 will probably cause just an ironic smile today, but nevertheless the scientists of that time have already been concerned about dynamic behavior of magnetic memory cells, and this interest resulted in an innovative and exciting time-resolved observation of magnetization dynamics using the strobing of sun light. The idea of using strobed light for optical studies of magnetization dynamics found the continuation in further works of other scientists back in that time [Kry69], where instead of sunlight a strobed laser light was used. In the same time dynamic domain imaging was done using a gated video camera [Pas68]. Back in 90-es time-resolved imaging was applied for the imaging of thin film magnetic reading heads [Pet90, Liu90]. Nowadays there is a wide variety of time-resolved microscopy methods. Most popular seem to be time-resolved scanning Kerr microscopy [Fre96, Sta98, Par03] and photo emission electron microscopy (PEEM) [Kuk04, Vog04, Sch04, Sch05]. Kuksov et. al. [Kuk04] report on 105 ps resolution. Another new powerful method for the study of magnetization dynamics is based on X-Ray dichroism. It allows high spatial and temporal resolution [Sto04, Choe04]. A fundamental research on precessional switching in pulsed field was also performed using the beam of a linear accelerator [Bac99]. Here the sample had been exposed to a magnetic field, produced by an accelerated electron bunch and the corresponding changes of the magnetization were imaged and analysed afterwards.

Time-resolved scanning Kerr microscopy has recently revealed many interesting and important details on

![Fig. 1.7 Calculated and experimentally observed switching of 15 nm thick 10µm x 2µm permalloy element. The observation was performed by means of time-resolved laser scanning Kerr microscopy. Both calculations and experimental images reveal strongly inhomogeneous and complicated domain patterns. Images taken from [Bal00].](image-url)
dynamic switching both by means of magnetization reversal and precessional switching [Sta98, Choi04, Choi01, Zel02, Hie02i, Hie02ii, Bue03]. Stankiewicz et al. [Sta98] imaged a switching of a 20 µm x 4 µm permalloy element and showed, that the reversal process may last as long as 30 ns, and that dynamic domain nucleation and growth are strongly inhomogeneous. Another set of solid experimental results is presented by Ballentine et al. [Bal00]. Here an experimental observation of the switching of a 10 µm x 2 µm permalloy element is compared to the analytically expected behaviour. The sample was simultaneously subjected to a negative DC field of –4.8 kA/m, and to a pulsed field with an amplitude of 12.8 kA/m. This resulted in a positive pulse of 8 kA/m, on the leading edge, and a negative pulse of –4.8 kA/m on the trailing edge. The resulting changes in the magnetization were captured with a temporal resolution of 50 ps. Some of the obtained experimental results and their comparison to a numeric simulation are shown in Fig. 1.7. In the calculated pictures one observes the presence of a very fine rippling on the y-component of magnetization. The observations confirm the presence of magnetization modulation in the y-direction (for quasistatic cases similar texturing is well known and understood [Hub98]). However, the experimentally observed rippling is not as fine and well defined as in the simulation. In Fig. 1.7 there also is some discrepancy between calculated and observed results. For \( t = 11 \text{ ns} \), for instance, the calculated behaviour of the x- and y-components is quite similar, i.e. we see distinct buckling on both images, whereas the measured x-component image does not reveal any buckling at all. The same is also true for other images of the series.

Low amplitude magnetization dynamics was studied by Park et al. [Par03]. There a Landau state was excited by a short field pulse and changes in magnetization were again imaged by laser scanning microscopy. It was shown, that the magnetization inside domain walls and inside homogeneously magnetized domains has different resonance frequencies. The oscillation frequency of moments inside domains was found to be about 2 GHz, whereas the frequency inside domain walls was only 700 MHz. This demonstrates, that high speed magnetization processes are dominated mainly by the rotation of magnetic moments and not by domain wall motion.

**Brief summary and objective outline**

- A deep insight into the dynamics on nanosecond time scale has already been achieved. Nevertheless, there are still many gaps in knowledge which ought to be covered in order to consider the subject
well understood. For instance, numerical calculations are still unable to reliably calculate the switching of structures larger than 5 µm. An adequate numeric solution of the micromagnetic equations requires a very high degree of discretization. The corresponding requirements on computer memory and processor speeds for larger elements often extend beyond the capabilities of currently available systems. Besides that, the reversal processes become more complicated with upscaling of the element’s size. This in turn requires even more thorough and elaborate solution methods and thus additionally re-enhances the complexity. As a result practically any numeric calculation of the reversal of the elements larger than 5 µm should be validated by experiment.

- *Scanning* Kerr microscopy has a good resolution potential, and has already provided outstanding results, but still imposes some limitations. With this method it is possible to obtain good snapshots of switching at several time steps, but it seems to be too formidable to acquire long series of images and to perform quasistatic imaging. Also, the time required for scanning is proportional to the sample’s area, which creates additional trouble for large sample imaging.

- Photo electron emission microscopy (PEEM) offers an excellent resolution, spatially as well as temporally. But at the same time it has an extremely limited possibility of field application. The only field, which can practically be applied, is the dynamic field of the stripline or coil. Combined with setup complexity and related costs, the limitations of these experiments make them not very suitable for systematic magnetization studies. The problem of high costs and restricted facility availability also applies to the X-ray dichroism magnetic microscopy.

- In this work the challenge of being able to perform combined and well-systematized studies of switching processes in magnetic thin film elements is addressed. A deep insight into both quasistatic and dynamic switching is delivered, and valuable estimates about corresponding similarities and differences between them are made. A good and reliable time resolution together with the possibility to apply magnetic fields (both fast and slow changing) is offered. This makes the approach a valuable and universal tool for thorough and systematic studies of magnetization dynamics in thin films.
2. Experimental

This chapter introduces the new approach for time-resolved microscopic studies of magnetization dynamics, based on combining a conventional Kerr microscope with a time-resolved intensified charge coupled device (ICCD) camera. It describes the most essential principles of the Kerr effect and of stroboscopic domain imaging, provides a detailed description of the experimental setup, sample construction, and some important calculations related to determining the bandwidth of the experiment and the strength of the pulse field.

2.1 Basics of the common Kerr microscopy

Magneto-optical Kerr effect

If a beam of linearly polarized light falls on the surface of a magnetic sample, then certain changes to the reflected light are introduced. Incoming photons excite the surface electrons. As a result the electrons begin to oscillate in the plane of the \( \mathbf{E} \)-vector of the light. If the oscillating electrons are subject to a magnetic field, they encounter a Lorenz force, which imposes a perpendicular component on the electrons’ motion. This component will result in an additional transverse light component \( R_k \), which effectively rotates the polarization plane of the reflected light. This rotation is utilized for the imaging of the magnetized samples. For a sample magnetized perpendicular to the surface, as shown in Fig. 2.1 (a), the plane of reflected or transmitted light will be rotated either right or left, depending on the magnetization direction. The phenomena of polarization plane rotation in reflected beam is called magnetooptical Kerr effect (MOKE). For the transmission case this phenomena is known as Faraday effect. In the same manner the polarization plane is rotated if the magnetization lays in the plane of the sample. If the magnetization vector is perpendicular to the plane of incidence and polarization plane, (Fig. 2.1. (b) ) then one speaks of parallel longitudinal Kerr effect. If the magnetization vector lays parallel to the plane of incidence, but perpendicular to the polarization plane (Fig 1.2. (c) ), then one is dealing with transverse longitudinal Kerr effect. The last case is shown in Fig. 2.1 (d). Here the magnetization is perpendicular to the incidence plane. This is the so-called transversal effect. The \( \mathbf{m} \times \mathbf{E} \) product is parallel to the polarization plane in this case, and thus it results in a change of the amplitude of the reflected light and not in a polarization plane rotation.
In this work always the longitudinal parallel contrast was used. By placing the analyzer on the way of the reflected beam one can detect the rotation of its polarization plane and thus obtain magnetic contrast. This contrast reveals the magnetization component that is parallel to the plane of incidence. For sensitivity in the transverse direction the transverse Kerr effect has to be used, or, alternatively, the sample has to be rotated by 90°. In this work the sample rotation is utilized. For the optimal detection of the Kerr rotation the planes of polarizer and analyzer have to be slightly misadjusted from their extinction position. The quantitative expression for the contrast is given by Hubert and Schäfer [Hub98]. It is shown, that the contrast is directly proportional to the strength of the Kerr rotation and to the normal intensity. This is why for obtaining a good Kerr image a bright light source is needed. The information depth of the Kerr method is about 20 nm for metals. Most informative are the top atomic layers of the sample, as the signal from deeper layers decreases exponentially. In context of this work the emphasis is made on films whose thickness does not exceed 50 nm. For such thin films the permeability in out-of-plane direction is extremely low due to a large demagnetizing factor. This yields two important consequences. First, the out-of-plane magnetization component is usually negligibly small, especially for quasistatic processes. For dynamic processes this component is expected to appear during magnetization precession but is still very small and does not produce a detectable contrast in the used setup. This point will become very important in section 2.3, where the field of the stripline is calculated and compared to experimental measurements. Second, the magnetization distribution in the domains is homogeneous across the sample’s thickness [Hub98]. Thus, the magnetic image seen on the surface delivers an adequate information about the magnetization of the entire sample. The exception to this rule are vortices, where the magnetization points out-of-plane regardless of film thickness. But they are just single points with a small area compared to the area of the
used samples, and do not cancel the general rule, which allows to assume the magnetization of the whole thin film sample to be completely characterized by the image seen on its surface.

**Kerr microscope**

The Kerr effect in the experimental setup is implemented in a Jenapol Zeiss microscope. This microscope delivers a wide field image of the object and does not use scanning. The corresponding simplified scheme is shown in Fig. 2.2. A high pressure xenon arc lamp is used as a light source. First the light beam follows through a system of condensing lenses, where it is compressed and optimized for further propagation through microscope optics. Then it passes through a Glan-Thomson prism polarizer to become linearly polarized. Afterwards the microscope optics projects the image of the arc on the objective’s back focal plane. The illumination settings correspond to a classical conoscopic microscope illumination (Köhler’s illumination) [Bey88]. A displaced slit aperture is set on the light’s path to acquire an oblique asymmetric illumination of the sample, as required for the longitudinal Kerr effect. Then the light passes through the objective and illuminates the sample. The reflected light bears magnetic information which is revealed as the light passes through the analyzer. Finally the optical information is collected by a CCD camera, or by direct eye observation. Throughout the experiments presented in Chapter 3 a 100x objective has been used, delivering a spatial resolution of 0.4 µm. For the experiments described in Chapter 4 a 50x objective with a numerical aperture of 0.75 was used providing a 0.5 µm optical resolution.

**Background subtraction and contrast enhancement**

The magnetic contrast obtained by Kerr microscopy is usually very low. This makes the obtained magnetic information often undistinguishable from the defects on the sample and other topographic features. For this
reason a difference imaging is performed, which is explained in Fig. 2.3. First a strong magnetic field that saturates the sample is applied, and then an image is taken. This image contains no domain information, but only topographic features and is called a background image. A similar effect may be obtained by application of an AC field and acquiring the background image over many oscillation periods, so that the magnetic contrast information averages out. Then a desired field is set and an image with domain information is acquired. Finally the background image is subtracted from the domain image, and as a result an image with pure magnetic contrast is obtained. All images in this work are grayscale images acquired with a 12-bit CCD camera. The best achievable magnetic contrast corresponds to some 25-40 grayscale in a 8 bit image, which is too little to effectively print and present the results. The problem is illustrated in Fig. 2.4. To make the images optically informative the contrast is additionally increased by stretching the image histogram. For this reason the intensity range of the informative pixels is stretched out in such a way, that the selected range occupies 8 bits of information (standard resolution for computers). The pixels, whose intensity is below the range, are set to black, the pixels with intensity above the range are set to white. The pixel intensities inside the informative range are linearly interpolated:

\[ I' = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \cdot 255 \]

where \( I_{\text{min}} \) and \( I_{\text{max}} \) are the boundaries of the informative range, \( I \) is the initial intensity, and \( I' \) is the reduced intensity. As a result the image becomes well adjusted for printing and publishing. For the image sequences
$I_{\text{min}}$ and $I_{\text{max}}$ are set for the entire sequence and not for each image separately. The histogram stretching operation is strongly non-linear. This is why all image measurements and intensity evaluations are performed on raw image data. Most of the domain images, presented further on, are integrated over a large number of exposures. The images are summed up in memory, that results in intensity values beyond 12 bit range. Further background subtraction may also lead to negative intensity values. That is why the suitable representation for the raw image data is signed 32 bit integer, but the resulting histogram of the printed pictures is still stretched down to 8-bit resolution.

2.2 Time resolved Kerr microscopy

Stroboscopic imaging

The main principle of stroboscopic imaging is shown in Fig. 2.5. The purpose is to image a fast magnetization switching process on the nanosecond time scale without interrupting it. For this reason the process runs continuously and uninterruptedly as the images at specified stages are obtained (symbolized by round circles). b) Final image with sufficient SNR after integration over a large number of process runs. Integration requires a high reproducibility of the studied processes.

Fig. 2.5 Principle of stroboscopic imaging. a) a process runs continuously and uninterrupted as the images at specified stages are obtained (symbolized by round circles). b) Final image with sufficient SNR after integration over a large number of process runs. Integration requires a high reproducibility of the studied processes.
rate, and thus the magnetization processes may be imaged only at a given set of frequencies. This reduces the use of this method to pulsed excitations only. The described below time-resolved experiment is built using a strobed camera instead of a strobed light source. The camera can function at variable frequencies, ranging from DC exposure up to 300 MHz. This allows to study dynamic processes without being bound to specific repetition rates. This also allows to study processes with continuous high frequency excitation, which is applied for the investigations on inductor elements.

**Time-resolved ICCD camera**

The camera, used for time-resolved imaging, consists of two parts: a photo intensifier and a conventional CCD chip-based camera. The whole camera setup is called Intensified Charge Coupled Device (ICCD) camera [LaV, Ken]. The scheme of it is shown in Fig. 2.6.

The incoming photons, which bear the optical information, hit the photo cathode of the intensifier. This results in the emission of corresponding photo electrons. The inner surface of the photo cathode is permanently kept under a positive potential of 50 Volts. This potential does not allow the emitted electrons to leave the cathode. Thus the initial optical information is not transmitted any further, the intensifier is in the closed state. On receiving an external trigger pulse the intensifier electronics produces

![Fig. 2.6 Schematics of the ICCD camera. A photocathode transfers incoming light into a photoelectron cloud. The cloud can propagate into a multichannel plate (MCP) only when a negative voltage is applied to it. By applying short pulses of negative voltage the intensifier can be used as an optical shutter. Inside the MCP the photoelectrons are accelerated and multiplied, where the degree of multiplication is determined by applied voltage. Afterwards the electrons are further accelerated and impinge on a phosphor layer, transferring the information back into optical form. The resulting image is captured by a conventional CCD camera.](image-url)
a short pulse of negative voltage with an amplitude of –200 V. This voltage enables the photo electrons to leave the cathode and enter a microchannel plate (MCP). The time resolution of such a system is determined by the effective opening time during which the electrons can propagate into the MCP. The MCP is a 1 mm thick plate with a hexagonal array of 12 µm holes. A variable positive voltage is applied between the entrance and exit planes of the plate to accelerate the electrons. The photo electrons collide with the surfaces of the holes, producing secondary electrons, which results in an electron cascade. The electron multiplication rate and thus the intensifier gain depends on the applied MCP voltage. The resulting electron cloud propagates further into a strong accelerating voltage of 6000 V. At the end the accelerated electrons impinge on the surface of a phosphor layer, which causes the emission of photons that can be integrated by a conventional CCD camera. The lens coupling system is an auxiliary optics that matches the image on the phosphor screen to the dimensions of the CCD sensor. In Fig. 2.6 it is shown just schematically and does not necessarily consist of just one lens.

Setup of the time-resolved microscope

The complete experimental setup is sketched in Fig. 2.7. The conventional wide-field Kerr microscope, whose functionality is described above, is the cornerstone of the entire experiment. By using the ICCD camera instead of a conventional CCD detector it is possible to perform time resolved dynamic observations. For the generation of the magnetic field pulses in the dynamic mode the coplanar waveguide-based samples are used. Their exact construction is described in section 2.3. The exciting signal is generated by a pulse- or
RF-generator. The wave is then fed into the waveguide using 50 Ω impedance, 18 GHz bandwidth cables with SMX connectors. The end of the stripline is terminated into an 20 GHz bandwidth sampling oscilloscope, where the signal is monitored. An alternative way to terminate the line is to use a 50 Ω terminator with corresponding bandwidth. The commercially available pulse generators are able to produce voltage pulses up to 45 V with a risetime of about 250 ps and a duration of up to 10 ns at a repetition rate of 1 MHz. It is also possible to acquire pulses with repetition rates up to 300 MHz and a risetime of about 90 ps, but this requires a trade-off on the amplitude, which then constitutes only 5 V. In the case of a continuous wave excitation amplitudes up to 15 V can be achieved by combining an RF generator with a broad band RF amplifier. The wave frequency may be set from 10 MHz up to 2 GHz (normally limited by the amplifier bandwidth). Besides the main waveform a generator also produces a reference or trigger signal, which is used for synchronizing the entire experiment. This signal is fed into a delay generator. Adjusting the delay between waveform and trigger signal allows to temporally scan through a process, as explained in Fig. 2.5. For repetition rates higher than 20 MHz an external 80 MHz bandwidth delay generator with a resolution of 25 ps is used. For repetition rates below 10 MHz an internal PCI-card based delay generator with a resolution of 25 ps is used. A careful calibration of the delay devices secures precise delay values in the range from 0 ns up to 100 ns. After delay setting the trigger signal propagates further and drives the image acquisition. To increase the sensitivity and the signal-to-noise ratio of the camera system the pixel binning was used, merging (hardware level) each pair of CCD pixels into a singe pixel (both horizontally and vertically) in the image and compromising on the spatial resolution of the experiment. As a result the spatial resolution was reduced to 0.8 µm for the dynamic imaging mode.

Time resolution of the experiment

Finding out the exact time resolution is a critical issue in this work, because the time resolution determines the bandwidth of the experiment and thus defines how fast a process can be effectively studied by the described approach. The calibration of the opening time of the photo intensifier was performed by temporal scanning of the optical signal produced by a pulsed laser. An empty sample holder of the microscope was externally illuminated by the laser, and the camera was registering the scattered light. Two different lasers were used: a semiconductor laser with a pulse width of 50 ps and a repetition rate of 1 MHz and a 20 ps mode-locked laser with a repetition rate of 23 MHz. This allowed to calibrate the time resolution for
the repetition rates typically used in this work. The shape of the actual intensifier optical exposure pulse is not a perfect rectangle, rather a Gauss impulse. This is illustrated in Fig. 2.8 (a). Here a brighter Gauss impulse represents the opening of the ICCD camera. The width in the middle of its amplitude is defined as effective exposure time. In the same manner the width of the laser pulse, which is also described by a Gauss function, is defined.

First it is shown, that the width of the laser pulse does not effect the measured response of the system. The response of the system is defined by the following expression:

\[ s(t) = u(t) \ast v(t) = \int_{-\infty}^{\infty} u(\tau)v(t - \tau)d\tau \]

Where the “\( \ast \)” sign represents the convolution operation, \( v(t) \) is the laser pulse function, \( u(t) \) is the probing pulse function, and \( s(t) \) is the convolution of the two signals. The corresponding Gauss functions may be defined in the following way:

\[ u(t) = A \exp(-\beta t^2) \]
\[ v(t) = B \exp(-\gamma t^2) \] (2.1)

Here \( A \) and \( B \) are the amplitude coefficients, \( \beta \) and \( \gamma \) are the parameters that define the width of the pulses. The effective width of \( u(t) \) and \( v(t) \) are defined as \( T_1 \) and \( T_2 \) respectively. The purpose is to prove that in case when \( T_1 \) is just a few times larger than \( T_2 \) then the measured width of \( s(t) \) is determined exclusively by the width of the probing pulse \( u(t) \):

![Fig. 2.8 Determining of the time resolution of the experiment.](image)

a) Scattered light of a narrow laser pulse (50 ps wide) is imaged by the ICCD camera. A system will detect an optical signal during the scan only when the laser and exposure pulses overlap in time, allowing to estimate the true opening time of the intensifier. b) The resulting signal is a convolution of laser and exposure pulses.
\[ s(t) = AB \int_{-\infty}^{\infty} \exp(-\beta \tau^2) \exp[-\gamma(t - \tau)^2] d\tau = \]

\[ = AB \exp(-\gamma t^2) \int_{-\infty}^{\infty} \exp(-\beta \tau^2 + 2\gamma t \tau - \gamma \tau^2) d\tau = \]

\[ = AB \exp\left[-\frac{\gamma \beta}{\gamma + \beta} t^2 \right] \int_{-\infty}^{\infty} \exp\left[-(\beta + \gamma)\tau^2 + 2\gamma t \tau - \frac{\gamma \tau^2}{\beta + \gamma} \right] d\tau = \]

\[ = AB \frac{\sqrt{\pi}}{\sqrt{\beta + \gamma}} \exp\left[-\frac{\gamma \beta}{\gamma + \beta} t^2 \right]. \]

Thus, the resulting response of the system is also described by a Gauss function:

\[ s(t) = C \exp(-\delta t^2) \quad (2.2) \]

where \( C = \frac{AB \sqrt{\pi}}{\sqrt{\beta + \gamma}} \) and \( \delta = -\frac{\gamma \beta}{\gamma + \beta} \). Expression (2.2) reveals that if \( \beta \ll \gamma \) then the width of \( s(t) \) is entirely determined by \( \beta \). For \( T_1 = 250 \) ps and \( T_2 = 50 \) ps the corresponding values for \( \beta \) and \( \gamma \) are \( 4.4 \times 10^{19} \) 1/s^2 and \( 1.1 \times 10^{21} \) 1/s^2, and thus the laser pulse width of 50 ps or less does not distort the measurement result. The calculated result is shown in Fig. 2.8 (b), where the scanning of the narrow laser pulse has reliably reproduced the probing signal. Figure 2.9 shows an experimentally measured response of the system. The effective width of the pulse is 290 ps.
During this experiment the delay generator had to be operated within a very wide range (delays from 0 to 1 µs). This resulted in an enormously high RMS jitter of 55 ps, measured directly by the oscilloscope. The true temporal resolution of the imaging system can then be derived by deducing 55 ps from the measured value, resulting in 235 ps (effective exposure time). The typical value of the electronic jitter during the measurements was determined to lay between 7 and 15 ps, and thus the time resolution of the experiment is no worse than 250 ps.

Knowing the effective time resolution of the experiment allows to determine its bandwidth, i.e. the frequency limit, which can be resolved by the method. For this reason the response of the system to a harmonic signal is calculated and the frequency behavior of the resulting function is analysed. For a general case the harmonic signal may assume the following form:

\[ g(t) = D \exp(i2\pi ft) \]

where \( D \) and \( f \) are the signal’s amplitude and frequency, respectively. To estimate the bandwidth, this expression has to be convolved with the camera response function \( u(t) \) from equ. (2.1):

\[
G(t) = g(t) * u(t) = AD \int_{-\infty}^{\infty} \exp[i2\pi f(t - \tau)] \exp[-\beta \tau^2] d\tau =
\]

\[
= AD \int_{-\infty}^{\infty} \exp[-\beta \tau^2 - i2\pi f \tau + i2\pi ft] d\tau =
\]

\[
= AD \exp(i2\pi ft) \exp(\frac{i^2 4\pi^2 f^2}{4\beta}) \int_{-\infty}^{\infty} \exp[-\beta \tau^2 - i2\pi f \tau - \frac{i^2 4\pi^2 f^2}{4\beta}] d\tau =
\]

\[
= AD \exp(i2\pi ft) \exp(-\frac{4\pi^2 f^2}{4\beta}) \int_{-\infty}^{\infty} \exp[-(\sqrt{\beta} \tau + i2\pi f \frac{f}{2\sqrt{\beta}})^2] d\tau =
\]
Thus the measured response appears as an original signal $g(t)$, multiplied by the constant $k$, and by the frequency-depend-
dent amplitude coefficient $\exp[-\frac{\pi^2 f^2}{\beta}]$.

The plot of this amplitude coefficient is presented in Fig. 2.10. The amplitude of the measured signal is decreasing exponentially. The decrease is determined by the relationship between the $\beta$-parameter, which determines the camera exposure time, and by the signal frequency $f$. As can be clearly seen from the plot, 2 GHz is the critical frequency that can reliably be resolved. Beyond this frequency the amplitude of the response is too small, and the measurement becomes not reliable. This point is illustrated in Fig. 2.11, where a numeric convolution of a sine wave signal with the camera response function is presented. The situation with our frequency resolution is very similar to the Nyquist theorem for digital signal processing. The fundamental conclusion of that theorem is that the resolution limit of a digital signal analyzing device is determined by half of its sampling frequency. The sampling frequency is the time distance between two subsequent samples of the signal, whereas the samples are assumed to have infinitely small width. If one violates this rule and attempts to resolve a signal, whose frequency components exceed half of the sampling rate, this will result in a so-called aliasing of the signal, where the high frequency components are strongly distorted. In the experiment described above the sampling frequency itself is not a problem, because the sampling can be performed at effectively 40 GHz, as determined by the resolution of the delay generator. The limitation however comes from the large width of the single sample. The signal, whose period exceeds the double period of the probing signal, can be resolved relatively well, as seen from the left column of Fig. 2.11. If the signal period is smaller than the double probing period, the amplitude during each sample is averaged out almost to zero, as can be seen from the right column in Fig. 2.11. Thus the highest resolvable frequency component is 2 GHz.

2.3 Samples for dynamic magnetic studies on shaped elements

Strip-line-based samples

The layout of the samples is presented in Fig. 2.12. The samples are based on a coplanar stripline. Such construction provides the possibility to generate fast changing fields on the nanosecond timescale. This assignment is impossible to accomplish using conventional electric magnets because of their large induc-
The only possibility to generate fast fields is to use a central conductor of a stripline as an electromagnet. A transient current pulse generates a pulse of magnetic field around the conductor. This field in turn drives the changes in magnetization of the thin film elements, which are deposited on top of the central conductor. The field strength calculation and experimental measurement are described in the next section. The cross section structure is shown in Fig. 2.13. A 270 nm thick Cu layer is deposited on a 600 µm thick Si/SiO₂ substrate. On top of the Cu layer 30 nm of Ta are deposited. Altogether these layers form a 300 nm conducting layer. The conducting layers are followed by 10 nm of Si₃N₄. This is an insulating layer, which prevents the current from flowing through the magnetic elements, and thus helps to keep a homogeneous current distribution. Additionally the intensity of the light reflected from the conductors is further attenuated. The following magnetic Fe₈₁Ni₁₉ (Permalloy) 50 nm layer is additionally covered by 3 nm Ta. This cap coverage prevents chemical oxidation of the sample, and also helps to match the reflection properties of the magnetic elements with those of the conducting environment.

The sample is produced in the following way: At first the Cu, Ta, and Si₃N₄ layers are sputtered on the Si/SiO₂ 3-inch wafer. Afterwards the layers are lithographically structured into a set of stripline elements by means of wet etching. In the next step all remaining layers are deposited, and the sample is further structured to obtain the set of magnetic elements on top of the conductors. This structuring is performed by means of optical lithography and subsequent ion beam etching. In the final step the wafer is covered with a protective lacquer and cut into separate samples. The samples are then mounted on special carriers, which allow to fasten them in the microscope and to feed high frequency excitations in. Both, samples and carriers, are designed to have a 50 Ω impedance. This is a most commonly accepted standard for high frequency cables, connectors and fittings. The generators, which feed the sample and the oscilloscope, into which the waveform is termi-
nated, also have a 50 Ω impedance. By matching all impedances we avoid parasitic reflections that might interfere with the signal and thus distort the measurement. The calculation of the transmission line parameters was performed with Appcad© software, issued by Agilent Technologies.

**Calculation of field strength**

In this section the magnetic field of the central conductor of a stripline is calculated. For calculation a direct integration of the fields, produced by elementary currents, is performed. A simple Cartesian coordinate system is used, as seen in Fig. 2.14. The conductor has dimensions of 2a and 2b. A small stripline element with coordinates (x,y) and current density j produces at the point (X,Y) the following radial field in A/m:

\[ dH(X,Y) = \frac{j \cdot dx \cdot dy}{2\pi \cdot r}. \]

Here an important assumption of a homogeneous current distribution was implicitly made. It is also assumed that the high-frequency field has the same strength as the calculated static field at a given current density. The confirmation for this presumption is given in the following section. As the current density is given by: \( j = \frac{I}{4ab} \) the above expression may be re-written as:

\[ dH(X,Y) = \frac{I \cdot dx \cdot dy}{8\pi ab \cdot \sqrt{(x-X)^2 + (y-Y)^2}}. \quad (2.4) \]

The longitudinal field component \( dH_x \) and the polar component \( dH_y \) are given by:

\[ dH_x = dH \cos \alpha \]
\[ dH_y = dH \sin \alpha. \]

The expressions for the trigonometric functions may be derived from the geometry:
\[
\cos \alpha = \frac{y-Y}{\sqrt{(y-Y)^2 + (x-X)^2}} \\
\sin \alpha = \frac{x-X}{\sqrt{(y-Y)^2 + (x-X)^2}}.
\]

After combining these expressions with equ. (2.4) and integrating the field over the entire volume of the stripline the following integrals are obtained:

\[
H_s(X,Y) = \frac{-I}{8\pi ab} \int_{-a}^{b} \int_{-b}^{a} \frac{y-Y}{(x-X)^2 + (y-Y)^2} \, dy \, dx, \quad (2.5)
\]

\[
H_i(X,Y) = \frac{I}{8\pi ab} \int_{-a}^{b} \int_{-b}^{a} \frac{x-X}{(x-X)^2 + (y-Y)^2} \, dy \, dx, \quad (2.6)
\]

Integrating equ. (2.5) over \(x\) yields:

\[
H_s(X,Y) = \frac{-I}{8\pi ab} \int_{-b}^{b} dy \int_{-a}^{a} dx \frac{y-Y}{(y-Y)^2} \left[ \frac{(x-X)^2}{(y-Y)^2} + 1 \right] = \frac{-I}{8\pi ab} \int_{-b}^{b} dy \int_{-a}^{a} \frac{d\left(\frac{x-X}{y-Y}\right)}{\left(\frac{x-X}{y-Y}\right)^2 + 1}
\]

\[
= \frac{-I}{8\pi ab} \int_{-b}^{b} dy \tan \left(\frac{x-X}{y-Y}\right) = \frac{-I}{8\pi ab} \left[ \int_{-b}^{b} \tan \left(\frac{a-X}{y-Y}\right) dy - \int_{-a}^{a} \tan \left(\frac{-a-X}{y-Y}\right) dy \right]. \quad (2.7)
\]

At this stage the \(dx\) is substituted by \(d(x-X)\). Further calculation is now reduced to the following integration:

\[
\int \tan \frac{1}{x} dx = x \tan \frac{1}{x} + \int \frac{1}{x^2 \left(1 + \frac{1}{x^2}\right)} x dx = x \tan \frac{1}{x} + \frac{1}{2} \ln \left(x^2 + 1\right).
\]

Here the partial integration was used. A further integration of equ. (2.7) may be split into two steps. A first integral yields:

\[
\int_{-b}^{b} \tan \left(\frac{a-X}{y-Y}\right) dy = \int_{-b}^{b} (a-X) \tan \left(\frac{a-X}{y-Y}\right) d\left(\frac{y-Y}{a-X}\right) =
\]
\[
= (a - X) \left[ \frac{y - Y}{a - X} \tan^{-1} \left( \frac{a - X}{y - Y} \right) + \frac{1}{2} \ln \left( \left( \frac{y - Y}{a - X} \right)^2 + 1 \right) \right] = \\
= (a - X) \left[ \frac{1}{2} \ln \left( \frac{(b - Y)^2 + (a - X)^2}{(-b - Y)^2 + (a - X)^2} \right) + \frac{b - Y}{a - X} \tan^{-1} \left( \frac{a - X}{b - Y} \right) -\frac{b - Y}{a - X} \tan^{-1} \left( \frac{a - X}{-b - Y} \right) \right].
\]

The second integral yields:

\[
\int_0^b \tan^{-1} \left( \frac{-X}{y - Y} \right) dy = \\
= (-a - X) \left[ \frac{1}{2} \ln \left( \frac{(b - Y)^2 + (-a - X)^2}{(-b - Y)^2 + (-a - X)^2} \right) + \frac{b - Y}{-a - X} \tan^{-1} \left( \frac{-a - X}{b - Y} \right) -\frac{b - Y}{-a - X} \tan^{-1} \left( \frac{-a - X}{-b - Y} \right) \right].
\]

The final expression for the longitudinal component of the stripline field may now be written as:

\[
H_x(X, Y) = -\frac{I}{8\pi ab} \left[ (a - X) \left[ \frac{1}{2} \ln \left( \frac{(b - Y)^2 + (a - X)^2}{(-b - Y)^2 + (a - X)^2} \right) + \frac{b - Y}{a - X} \tan^{-1} \left( \frac{a - X}{b - Y} \right) -\frac{b - Y}{a - X} \tan^{-1} \left( \frac{a - X}{-b - Y} \right) \right] \\
-(-a - X) \left[ \frac{1}{2} \ln \left( \frac{(b - Y)^2 + (-a - X)^2}{(-b - Y)^2 + (-a - X)^2} \right) + \frac{b - Y}{-a - X} \tan^{-1} \left( \frac{-a - X}{b - Y} \right) -\frac{b - Y}{-a - X} \tan^{-1} \left( \frac{-a - X}{-b - Y} \right) \right] \right].
\] (2.8)

In exactly the same manner the polar component of the field is calculated. The final expression for it may be written as following:

\[
H_y(X, Y) = \frac{I}{8\pi ab} \left[ \left( b - Y \right) \left[ \frac{1}{2} \ln \left( \frac{(a - X)^2 + (b - Y)^2}{(-a - X)^2 + (b - Y)^2} \right) + \frac{a - X}{b - Y} \tan^{-1} \left( \frac{b - Y}{a - X} \right) -\frac{a - X}{b - Y} \tan^{-1} \left( \frac{b - Y}{-a - X} \right) \right] \\
-(-b - Y) \left[ \frac{1}{2} \ln \left( \frac{(a - X)^2 + (-b - Y)^2}{(-a - X)^2 + (-b - Y)^2} \right) + \frac{a - X}{-b - Y} \tan^{-1} \left( \frac{-b - Y}{a - X} \right) -\frac{a - X}{-b - Y} \tan^{-1} \left( \frac{-b - Y}{-a - X} \right) \right] \right].
\] (2.9)

Expressions (2.8) and (2.9) completely describe the spatial distribution of the magnetic field. With their help a picture of magnetic force lines may be derived, as displayed in Fig. 2.15. The calculation is performed for a stripline with dimensions as used in the experiments. A current of 0.02A was assumed, which
Fig. 2.15 Calculated magnetic field of the 42 µm x 300 nm stripline.

Fig. 2.16 Profiles of calculated magnetic fields. a) longitudinal and polar field components on the conductor surface as a function of x-position. Longitudinal component is zero outside the stripline; on the edge of the stripline it rapidly reaches a value of 229 A/m and slowly grows to its maximum value of 235 A/m, which is reached in the middle. Such behaviour is equal for both sides. The polar field component reaches its maximum amplitude of 400 A/m on the conductor’s edge; its amplitude decreases across the conductor width and reaches a zero value in the middle of the stripline as a function of vertical distance. The longitudinal field has its maximum on the conductor surface (zero-distance). With increasing distance the field strength decreases.
corresponds to a voltage pulse of 1 V into the 50 Ω-terminated line. Figure 2.16 shows the longitudinal and polar field components as functions of x-position on the surface of the conductor. The strength of the longitudinal field equals zero outside the conductor. On its edges it grows very steeply to a value of 229 A/m, and remains very homogeneous across the stripline. A maximum value of 235 A/m is reached in the middle of the strip. The homogeneity of the longitudinal field distribution is of critical importance, since otherwise the experimental results would be almost impossible to interpret. The behaviour of the polar field component is opposite to that of the longitudinal component. The polar component reaches its maximal value on the left edge of the stripline. It decreases rapidly with increasing x-coordinate. The zero-value is reached in the center of the strip, exactly at the point where the longitudinal component reaches its maximum. Then the polar field strength increases in the negative direction and reaches its minimum value on the right edge. The amplitude value of the polar field is almost double that of the longitudinal field. It might seem, that this kind of inhomogeneous field might cause a strongly inhomogeneous magnetization distribution in the magnetic samples on top of the stripline. But this is not the case, since for the thin film samples used in this work the polar demagnetizing factors are much greater than the in-plane ones. This in turn means that the polar permeability is very low, and the sample cannot be magnetized out-of-plane. This is why the magnetic behaviour is completely dominated by the homogeneous longitudinal field.

The magnetooptical approach makes it possible to experimentally measure the stripline field. This can be done in two ways. The first way relies on magnetooptical hysteresis loop measurements, in which the Kerr signal intensity is recorded as the external magnetic field reverts the sample from one saturated state into the opposite one. In the absence of a bias field the loops of the elements are symmetric and not shifted. An application of a slight DC voltage to the stripline results in a small bias field, which displaces the hysteresis loops. By measuring this displacement it is possible to directly gain information about the stripline field strength. Another method is even simpler. At first an element is demagnetized in an external AC field, so that a Landau state is formed at zero field. The picture of this state is saved in the image processor memory as a reference image. If a DC current flows through the stripline, the resulting field will displace the vortex and domain walls of the Landau state. This displacement causes a strong contrast on the difference image, delivered by the image processor. By applying an external DC field with an electromagnet it is possible to compensate this domain displacement till the contrast in the difference image disappears. The required external field should exactly equal the field of the stripline. This method is applicable only to those elements,
which do not demonstrate hysteresis for slight domain displacements around zero field. Both methods deliver very close values. For a 42 µm wide stripline the measured field, produced by a current of 0.02 A, equals 217 A/m, whereas the calculated field is 235 A/m. For a 93 µm stripline a field of 105 A/m was measured, while the calculation predicts 107 A/m. These values are in very good agreement.

**Remarks about fields and waves in the stripline**

The transition of a high frequency signal in a coplanar stripline, as well as in a coaxial cable must be considered in terms of wave propagation and not in terms of electrical conductivity. In a coaxial cable electromagnetic waves propagate between the central conductor and the shielding. The basic type of waves are TEM (transverse electromagnetic) waves, in which the magnetic and electric field vectors oscillate perpendicularly to the propagation vector. The critical wave vector for these waves is equal to zero, which means that TEM’s appear beginning from zero frequency. Grigorjev [Gri90] shows, that in spite of the complicated wave picture, the expression for the strength of a high frequency magnetic field is given by the same expression as the strength of the magnetostatic field. In case of a coplanar stripline the quasi-TEM waves are propagating. These waves possess a magnetic vector component, which is parallel to the propagation direction. This component, however, is much smaller than the transverse component of the wave [Gri90]. Altogether these considerations justify the field calculation using a magnetostatic model.

Also the assumption of a homogeneous current distribution at high frequencies was implicitly made. This point, however, should also be confirmed. A problem could be caused by the skin effect, i.e. at high frequencies the electric field is expelled from the interior of the conductor, and thus the current is flowing only on its surface. Grigorjev [Gri90] thoroughly studies this point by direct solution of the Maxwell equations of propagating waves in metals. This study demonstrates, that for magnetic waves the metal plays the role of a very dense optical medium with penetration depth being the following function of the wave frequency:

\[ \delta = \sqrt{\frac{2}{\omega \mu_0 \vartheta}} \]

where \( \delta \) defines the depth, at which the wave amplitude decreases by a factor of \( e \) (\( \omega \) is the circular frequency, and \( \vartheta \) is the conductivity). For copper the skin depth at 10 GHz equals 0.66 µm and at 1 GHz
it equals 2.1 µm. The stripline used in this work has a thickness of just 300 nm, and the frequency range
does not exceed 2 GHz, which means that the skin effect does not play any role. This completely justifies
the assumption of a homogeneous current density.

Figure 2.17 shows the S11 and S12 parameters of the used stripline, measured
by the 3 GHz bandwidth network
analyser. These parameters characterize
energy losses, caused by reflections and
damping, respectively. The damping at
low frequencies equals 0.6 dB, and is
introduced by the Ohmic resistance of the
stripline. At frequencies between 400 and
700 MHz the damping increases up to
1.4 dB. At a frequency of 1 GHz the
damping reduces back to 0.6 dB, which confirms the absence of the skin effect in this frequency range,
otherwise the damping would not decrease. Beginning at 1.3 GHz the damping slowly increases, but this
increase is due to increasing reflections, which are represented by the S11 curve. This means that the
stripline impedance was not perfectly matched, and that the frequencies above 1.3 GHz are partially
reflected from the 50 Ω load. But their amplitude is still very low, and they do not introduce any measurable
distortions to the optical imaging results. The only influence of this mismatch is the fact that the stripline
partially filters the high frequency components. For a pulsed field this results in an increase of the rise time
of the pulse from 280 ps, as delivered by the generator, up to 350 ps, because sharp waveform edges are
mainly determined by high frequency components. For harmonic excitations simply a calibration of the
signal amplitude for a specific frequency is required, otherwise no further distortions are introduced.
Conclusions

- Conventional Kerr microscope is used to obtain magnetic contrast. The microscope delivers images with 0.4 µm resolution in the quasistatic imaging mode. In the dynamic mode the use of pixel binning reduces the spatial resolution to 0.8 µm.

- A gated ICCD camera delivers a 235 ps time resolution that was confirmed by direct measurements. The entire experiment has a resolution of 250 ps, caused by additional jitter of pulse- and delay generators.

- Processes with a bandwidth up to 2 GHz can be reliably studied. Imaging of processes at higher frequencies will result in a rapid decrease of the measured signal and thus unreliable imaging.

- Time-resolved imaging requires integration over many switching events to obtain an acceptable SNR, thus also requiring a high reproducibility of the studied processes.

- The magnetic field of the stripline has a clear analytic expression. This enables to exactly know the strength of the dynamic field at any given moment of time by knowing the waveform of the electric excitation.

- The longitudinal component of this field is very flat and homogeneous across the stripline width. This excludes possible artifacts in the magnetization behaviour that may be caused by inhomogeneous field strength distribution and further interfere with the interpretation of the obtained results.

- The polar field component on the edges of the sample is twice as strong as the longitudinal one and is strongly inhomogeneous. This component reaches its minimum and maximum values on the opposite ends of the stripline cross section, reaching a zero value in the middle.

- Nevertheless, the polar field does not interfere with the magnetization processes, because the corresponding demagnetizing factor of the thin film elements is very strong, reducing the effective
permeability of the sample in the polar direction. This allows to make a statement, that the observed
dynamic processes are due to the in-plane field of the stripline. Such statement facilitates the evaluation
and interpretation of the measured data.
3. Dependence of the switching behaviour on the geometry of field application and the shape of the elements.

This chapter contains experimental results performed on 50 nm thick permalloy elements of different shapes and their interpretation. The main emphasis is set on the comparison between quasistatic and dynamic processes in given elements. The key problem, addressed in context of this comparison, is to figure out the influence of elements’ shape on their dynamic behaviour and switching speed.

3.1. Square shaped element in fields applied along the diagonal direction

Quasistatic switching

A quasistatic study of this element provides valuable information about the formation and development of a classical 4-domain Landau state. Figure 3.1 presents the corresponding optical information about the quasistatic reversal process. It contains two rows of domain images, acquired with different directions of Kerr sensitivity. In the upper row the sensitivity axis is vertical, i.e. parallel to the axis, along which the slowly changing external field is applied. Therefore, the images

![Fig. 3.1 (a) through (f) Quasistatic reversal process in a square element in an externally applied diagonal field. Upper row: images with longitudinal sensitivity; middle row: images with transverse sensitivity; bottom row: schematic interpretation of magnetization patterns derived from the Kerr contrast.](image-url)
in the upper row reveal information about magnetization components parallel to the field. The middle row contains images with the Kerr sensitivity oriented horizontally, and thus perpendicular to the applied field. The images with different sensitivities were not acquired simultaneously (unlike in scanning Kerr microscopy), rather sequentially. At first the longitudinal sensitivity image series was acquired. After this the sample was rotated by 90°, and the same reversal was imaged with the transverse sensitivity. The possible differences between the two image series are very insignificant, since most critical features of the reversal processes in low-anisotropy soft magnetic elements are mainly determined by their shape and external field change, and hence are well reproduced. This provides a reliable correspondence between the domains seen first with longitudinal and then with transverse sensitivities. The bottom row contains a schematic interpretation of the domain structures observed.

Initially, a positive field of 2.5 kA/m is applied upwards, and then slowly reverted. This drives the element from positive to negative saturation. The switching process begins with a slight rotation of magnetization, as shown in Fig. 3.1 (a) in the transversal image. An increasing rotation [Fig. 3.1 (b)] leads to the formation of a metastable magnetization distribution, called concertina pattern [Ber82] or buckling state [Hub98]. Trying to minimize the stray field energy the magnetic moments rotate clock- and counter clockwise in an alternating way, resulting in the formation of a magnetic texture orthogonal to the average magnetization direction. This structure can be interpreted as a system of low-angle Néel walls, stabilizing each other by dipolar fields. A characteristic feature of the concertina state is a low mobility. As the process proceeds and the external field decreases almost to zero [images (b) and (c)], the magnetization rotation increases, but no domain wall motion is observed. As the external field reaches a critical value, the concertina state irreversibly collapses by the formation or unpinning of multiple Bloch lines at the edges of the element, resulting in the formation of a classical Landau state [image (d)]. With further reversal the domains, which are magnetized parallel to the applied field, grow at the expense of those, which are magnetized antiparallel, reducing the element’s energy. The growth of domains proceeds by domain wall and vortex motion and is very sensible to changes in the external field [(d) and (e)]. At the final stage of reversal the element basically assumes a single domain state again, but the magnetization distribution is yet not perfectly homogeneous, because demagnetizing fields hinder the magnetic moment at the
edges from a perfect alignment with the applied field [state (f)]. Only stronger fields (2.5 kA/m and more) are able to remove the magnetization rotation. Over the course of multiple experiments the described switching manner has demonstrated a very high reproducibility.

**Dynamic switching**

The element, whose quasistatic behaviour was described in the previous section, was exposed to a rapidly changing pulsed magnetic field. The pulses had an amplitude of 8.3 kA/m, a length of 10 ns and a rise time of some 350 ps. This is a unidirectional positive field, applied along the vertical diagonal of the element [Fig. 3.2]. In order to provide a complete reversal process, an additional negative bias field of –2 kA/m, which opposes the pulse field, was applied. The resulting magnetic field profile is shown in Fig. 3.2 (k) as a grey shaded region. In the absence of the magnetic pulse the sample is saturated negatively by the bias field. This field may not necessarily be able to completely remove magnetization curling on the edges [similar to Fig. 3.1 (f)], but it keeps the sample in a single-domain state that can be considered saturated. On arrival of the positive pulse field the total resulting field has an amplitude of 6.3 kA/m and drives the sample into the positive saturation. After the offset of the pulse the remaining bias field drives the sample back into negative saturation.

The images, containing the dynamic information, are collected in Fig. 3.2 (a) through (j). As in the quasistatic case, the images with longitudinal and transverse sensitivities (upper and middle rows) are presented together with a qualitative interpretation of the arising domain structure and magnetization distribution (bottom row). The presented images correspond to the rising and falling edges of the pulse, the letter indices of the images correspond to the markers of data points on the Kerr signal curve in Fig. 3.2 (k). The negatively saturated state in the absence of the pulse field is shown in image (a). After arrival of the positive pulse field the beginning of switching is characterized by a magnetization rotation on the sides of the element [image (b)]. This rotation increases, leaving the central part of the element still unchanged (c). The switching of the central part proceeds much slower and lasts several nanoseconds. At first the unswitched area becomes narrower (d), and finally dissolves as the sample reaches its positive saturation (e). The switching proceeds basically
Fig. 3.2 Dynamic reversal of a 50 nm thick square permalloy element in diagonally applied field. (a)—(j): Kerr images with longitudinal and transverse sensitivities together with schematic interpretation of magnetization distribution, derived from Kerr contrast. The switching is driven by a superposition of a –2 kA/m DC field and a +8.3 kA/m pulse field. (k) effective driving field (grey-shaded area) and switching curve, derived by measuring the longitudinal Kerr signal intensity over the element’s area. The letter markers correspond to the presented images.
by means of incoherent magnetization rotation, as shown in the schematic interpretation of the process. Regions with different rotation degree appear as domain-like areas [most clearly seen in (c) and (d)]. Unlike quasistatic domains the dynamic ones are not separated by sharp and clear-cut domain boundaries, rather by fuzzy domain walls [Chu05]. The Kerr signal plot on the rising edge reveals that in spite of some delay, caused by the slow switching of the middle part, the magnetic signal still follows the fast changing pulse field quite closely. This, however, is not the case for the slower trailing edge of the pulse, where a strong delay between pulse field and magnetization response is observed. The peculiarities of the trailing edge switching also bear some strong differences. As in the case of the rising edge the first changes arise in form of magnetization rotation, symmetrically localized on the sides of the element. However, not only the central part, but also the left and right corners of the element are prevented from rotation over a long time span [images (g) through (j)]. A careful consideration of both, longitudinal and transverse images yields a comprehensive interpretation for the complicated switching process. In the beginning the magnetic moments rotate parallel to the element’s edges [state (f)], as dictated by relatively strong local demagnetizing fields. This initial rotation gradually grows into a concertina pattern [state (g)]. As the switching proceeds, the concertina becomes sharper and its transversal contrast increases [states (h) and (i)], indicating an increase of clock- and counter-clockwise rotation. The concertina itself seems to be almost equal to the one observed during quasistatic switching of this element. However, the corresponding set of longitudinal images reveals a strong qualitative difference between the dynamic and quasistatic cases. Whereas the concertina state in the quasistatic case is resolved into a Landau state by means of abrupt domain wall motion, the dynamic concertina pattern is resolved through a gradual and continuous rotation towards the negative direction, retaining the magnetization texture that is still clearly seen in the transversal images [(h) and (i)]. In the longitudinal images this rotation process leads to the formation of symmetric bright regions in the left and right halves of the element [states (g) and (h)]. As the switching proceeds these regions grow in size [(i) and (j)], at the same time the concertina state is slowly and gradually dissolving.

The reason why the magnetic response of the sample can follow the fast rising edge of the pulse almost undelayed, but cannot follow the relatively slow trailing edge immediately, is given by the absence and presence of the concertina state respectively. As stated before, concertina states are
very robust, as their stability is sustained by magnetic charges, which inevitably accompany Néel walls. This introduces an effective magnetization blocking, and thus the dynamic process is slowed down. The reason why such a multidomain state is pronounced much stronger on the trailing edge of the pulse is given by corresponding differences in the effective driving field amplitudes and differences in the rising and falling edge speeds. The element is initially saturated downwards by the relatively weak bias field $H_{\text{bias}} = -2 \text{kA/m}$. The incoming pulse excitation with a fairly sharp rising edge and positive amplitude of 6.3 kA/m forces a rapid magnetization rotation, especially in those regions, where the influence of local demagnetizing fields, which promote rotation, is strongest and the influence of demagnetizing fields, which hinder rotation, is weakest. These favourable conditions are obviously met on the sides of the element since these regions switch at first. The formation of concertina pattern involves building of a complicated interacting network of domains. At the abrupt onset of a strong pulse field the element simply does not have enough time to do so. The moments are forced rather to a massive incoherent rotation on the sides, leading to the unswitched area in the middle. On the falling edge the excitation is not as sharp and rapid, and not as strong in the amplitude. This gives the magnetization enough time to form a charged wall network and wind up with an immobile multidomain state, very similar as in the quasistatic case. Also vortex-like structures are formed in the vicinity of the left and right corners, whose formation is stipulated by topological reasons, as the magnetization rotation in the corner is strongly hindered. The breakdown of the given multidomain concertina would require a simultaneous unpinning of multiple Bloch lines, which is a very slow process that cannot take place on the nanosecond timescale. Therefore, the further switching proceeds by incoherent rotation, rather than by wall and vortex motion like in the quasistatic case.

To prove these arguments the $H_{\text{bias}}$ was reduced to $-4 \text{kA/m}$, providing a positive pulse of 4.3 kA/m and thus a quite symmetric excitation in both negative and positive directions, as shown in Fig. 3.3. With the symmetry in the exciting fields also a corresponding symmetry in the sample’s dynamic behaviour is expected. The beginning of the process on the rising edge is again characterized by a rapid magnetization rotation, which leads to formation of domains [states (a) and (b)]. But in this case the external field energy is weaker and not strong enough to violently remagnetize the entire sample by means of massive rotation (as in the previous case). After formation of initial domains
the further reversal proceeds by a combination of domain wall motion and rotational processes, which are strongly hindered by the reduction of the effective torque, caused by demagnetizing fields on the edges, and charges of low-angle domain walls. Altogether it strongly reduces the speed of further switching (the corresponding kink in the Kerr signal plot on the rising edge appears in Fig. 3.3 (f), which is absent in Fig. 3.2 (k). The rise time of the sample response is now about 2.1 ns. The overall rising edge behaviour is characterized by slow domain annihilation [states (a) and (b) in Fig. 3.3], and qualitatively corresponds to the sample behaviour along the falling edge in low bias field [Fig.3.2 (g) trough (j)]. The switching speed on the falling edge of the pulse has also become much faster, compared to the case with $H_{\text{back}} = -2$ kA/m. Now the fall time of the sample’s response becomes much shorter and equals just 2.9 ns. The vortex-like structures and concertina are formed on the falling edge as well. Compared to the previous case some additional magnetization rippling is introduced in the left and right corners of the sample. Nevertheless, the overall strength
of transverse magnetization buckling is significantly reduced as compared to the case shown in Fig 3.2. Another important qualitative difference follows from comparing the magnetization distributions in the right and left corners of the element. For the symmetric pulse on both, rising and falling edges [Fig. 3.3 images (a), (b), and (e)] , the vortex-like domain structures occur, leaving these areas almost unswitched. This confirms the conclusion, that the rotation speed on the edges is strongly reduced because of strong local demagnetizing fields. These fields have the same strength and influence in both cases. In this case, however, the influence of the demagnetizing is more evident, because it is no more exceeded by a strong and sharp field on the rising edge. Altogether, by making the field strength on the leading and trailing edges of the pulse quite symmetric, also a more symmetric magnetization behaviour was obtained.

The results on the influence of the magnitude of the driving field on the switching speed of the elements are summarized in Fig.3.4 Here the corresponding rise- and fall times of the diagonal square element are plotted as a function of the field magnitude. The switching at high field is relatively fast and occurs typically within a sub-nanosecond time. For low amplitude driving fields the switching requires some nanoseconds. Another important point is the absence of a speed dependency on the pulse edge shape. The switching speeds at given driving field values are approximately equal for both rising and falling edges of the pulse, although the corresponding edge profiles are different. Thus, the pulse amplitude is the determining factor for the switching speed. Only at a small driving field [2 kA/m, Fig.3.2 (k) ] the shape of the pulse on the falling edge produces a corresponding influence on the switching speed of the element. The temporal change of the driving field in this case is extremely slow, which makes the reversal also slow. For higher driving field amplitudes there was no dependency on the pulse shape detected.
The attempts to observe the change of the out-of-plane magnetization component during the dynamic switching have unfortunately been unsuccessful. The reason for this is the insufficient magnitude of the polar magnetization component to produce a detectable contrast in the imaging system.

3.2 Square shaped element in fields applied along the vertical edge

**Quasistatic switching**

Figure 3.5 shows images of a square 40µm x 40µm element with slowly changing magnetic field applied along the vertical direction. This external field drives the sample from positive to negative saturation. The switching process is initiated by magnetization rotation at the top and bottom edges of the element [state (a)], where the effective torque, acting on the magnetic moments, is strongly reinforced by local vertical demagnetizing fields. This is different from the case of diagonally applied field [Fig. 3.1]. The reversal proceeds further by the formation of a concertina pattern, which gradually penetrates into the middle of the element [states (b) and (c)]. Here the transversal magnetization texture is not as fine as in the case of the diagonal element, because the influence of horizontal demagnetizing fields, which tend to confine rotation, is weaker. This enables larger
regions to rotate clock- and counter-clockwise without a strong stray field energy penalty. Thus the period of the concertina pattern becomes larger (see states (b) and (c) of Fig. 3.1 for comparison). A further field change leads to a collapse of the concertina state and results in the formation of a classical 4-domain Landau pattern (d), exactly as it was in the diagonal element. Also the further process development is very similar and is reduced to domain wall motion (e). As the vortex is driven out of the element and no domains are left, the magnetization on the top and bottom edges is still not aligned vertically (f), due to demagnetizing fields, which now inhibit rotation. Nevertheless, just like in the case of the diagonal element, this state may be considered as switched.

**Dynamic switching**

Though the quasistatic behaviour of this element is fairly simple and clear, its dynamic switching is not as clear. Nevertheless there are some features and trends, which can be noticed and interpreted. Figure 3.6 presents images of the dynamic reversal [(a) trough (j)] together with the corresponding Kerr signal (k) produced by the element. The experimental conditions, to which the sample was exposed, are the same as in the previous case (Fig. 3.2). This allows a direct comparison of the influence of the shape. From the states (a) through (d) it follows, that the rising edge switching occurs in nearly 1 ns. However, the images with both, longitudinal and transverse sensitivity directions, barely reveal a well defined and clearcut magnetization distribution or domain pattern during this reversal. The beginning of the reversal is somewhat similar to that of the quasistatic process, where the first noticeable rotation appears at the top and bottom edges of the element, being stimulated by strong local demagnetizing fields. The further reversal takes place by a magnetization turnaround in the center of the element (state (c), longitudinal image). The transverse image of state (c) demonstrates the presence of a slight magnetization rippling. In state (d) the sample has reached a 70 % signal level. There is some vague contrast seen inside the element in both images, especially in the transversal one. This contrast might be due to numerous rotational processes, which are still going on, but might be not very well resolvable with the 250 ps exposure time, or are not reproducible enough to generate a clear image over a large number of integrations. Also this contrast might even be an indication for the presence of spin waves that simply stay beyond the experiment resolution range both temporally and spatially. Also some edge domains
Fig. 3.6 (a)—(j) dynamic reversal of a 40µm x 40µm 50 nm thick permalloy element. The field is applied along the vertical direction. The effective field (shown as grey area in (k)) consists of a superposition of a –2 kA/m negative bias field and a 8.3 kA/m positive pulse field. Shown are images with parallel and transverse sensitivities, accompanied by a schematic interpretation of domain patterns. The data markers on the switching curve correspond to presented images and reflect the Kerr signal intensity measured in the entire element.
are present on the right and left sides of the element, which can be best seen in the longitudinal image. These domains require a significant amount of time to completely annihilate, slowing the entire sample response down. The switched state with annihilated edge domains is presented in image (e).

Images (f) through (j) in Fig.3.6 correspond to the falling edge of the pulse. The overall course of the reversal process seems to be quite similar to the rising edge, except for the presence of a well defined rippling structure (states (g) through (j)). This structure is similar to that observed in the element with diagonal field [Fig. 3.2 (g) through (j)]. This rippling is also much finer than that observed during the quasistatic process for the same element (Fig.3.5 (c)). The edge domains, seen in the longitudinal images, are much stronger pronounced than they were on the rising edge and vanish slowly. The falling edge reversal lasts several nanoseconds and is slower than the rising edge one. The further decrease of the negative bias field to –4 kA/m leads to an equalization of negative and positive pulse amplitudes, resulting in an equalization of the switching speeds on the rising and falling edges [Fig.3.7 (a)]. For both edges the reversal occurs in a sub-nanosecond time span. As in the case of diagonal field, a further decrease of the bias field does not result in a significant increase of the switching speed [Fig. 3.7 (b)]. The overall comparison of data in Figs 3.4 and 3.7 (b) yields the conclusion, that the switching processes are much faster in case of the vertically applied field. The overall qualitative difference between the two cases is that concertina states are much stronger emphasized in case of diagonally applied fields (derived by comparison of Figs 3.2 and 3.6). Thus it confirms the empiric conclusion that the presence of multiple low angle domain walls is responsible for an additional inhibition of the switching processes.

![Fig. 3.7. a) Kerr signal of the element with a bias field of -4 kA/m. b) dependence of the switching speeds on the rising and falling edges as a function of the driving field amplitude.](image-url)
3.3 Rectangular 40µm x 28µm element

Reducing the element’s width while keeping its height constant accomplishes another step in increasing the shape anisotropy. This change in turn triggers changes in the element’s switching behaviour.

Quasistatic switching

Figure 3.8 contains a set of images of the quasistatic reversal of a 40µm x 28µm element. The remagnetization initiates at the top and bottom edges of the element as a rotation [state (a)]. As this rotation increases it proceeds further towards the interior of the element [state (b)]. This is accompanied by a formation of a low mobility concertina state. The concertina blocks the whole process for a while, i.e. as the external field continues to decrease there are no additional changes in the domain structure [states (c) and (d)]. As the field reaches a certain critical value the blocking state collapses and the reversal proceeds by domain wall motion [(e) through (g)]. Thus, the overall reversal progress does not qualitatively differ from that in a square element with a vertically applied field. Nevertheless, there are some evident quantitative differences in the switching field strengths and concertina periods. In the case shown in Fig. 3.5 the breakdown of the concertina occurred at –0.1 kA/m field, whereas the concertina pattern in the 3:2 element remains stable in the same field [Fig. 3.8 state (d)].

Dynamic switching

Figure 3.9 contains a set of dynamic images of the reversal process. This process exhibits a lot of similarities to that of the square element in its overall behaviour, but also contains certain differences. The reversal begins in a similar way by magnetization rotation at the top and bottom edges [state (a)]. Afterwards the middle part of the element becomes involved into magnetization turnaround. But this time a very noticeable concertina state is present along the rising edge of the pulse [states (b) and (c)], as can be seen in the transversal images. The rising edge rotation processes in the images with longitudinal sensitivity appear in the same way as for the square element, where no
Fig. 3.9 (a) through (f): images of dynamic reversal process in 40µm x 28µm element with vertically applied field. Upper row: images with longitudinal sensitivity; middle row: transversal sensitivity; bottom row: schematic interpretation of magnetization distribution.

Fig. 3.8 (a) through (g): Quasistatic switching of a 50 nm thick rectangular 40µm x 28µm (3:2) permalloy element in external field. Top row: images with transverse sensitivity; bottom row: schematic interpretation of domain structure and magnetization distribution.

Fig. 3.9 (a) through (f): images of dynamic reversal process in 40µm x 28µm element with vertically applied field. Upper row: images with longitudinal sensitivity; middle row: transversal sensitivity; bottom row: schematic interpretation of magnetization distribution. (g): Kerr signal plot as a function of time together with the waveform of the driving field (shown in grey).
specific domain pattern can be detected. The falling edge behaviour of the elongated elements is again characterized by the formation of a strongly emphasized ripple structure and by edge domains at the right and left sides of the element [states (d) through (f)]. The density of rippling in the 3:2 element is significantly higher than in the square element; the same is true for the area occupied by the edge domains relative to the area of the whole element, which is larger than in the square element. Both factors contribute to the inhibition of the switching along the falling edge. Now the falling edge switching lasts some 6.5 ns (5.5 ns for the square element). Setting the bias field to $-4 \text{kA/m}$ results in a further change of the switching speeds on both rising and falling edges [Fig. 3.10].

3.4 Rectangular 40µm x 10µm element

Fig. 3.11 50 nm thick rectangular 40µm x 10µm (4:1) permalloy element in slowly changing external field. Top row: images of the quasistatic switching with transverse sensitivity; bottom row: schematic interpretation of domain structure.
Quasistatic switching

To strongly emphasize the influence of shape anisotropy on the reversal processes a further increase of the element’s aspect ratio up to 4:1 was made. This strongly increases the influence of horizontal demagnetizing fields all over the element. The corresponding quasistatic switching process is shown in Fig. 3.11. The slow reversal process contains no qualitative differences to the previous case of the 3:2 element. The process begins with a magnetization rotation at the top and bottom edges of the element [state (a)], which increases and grows into a concertina structure [states (b) through (d)]. At a critical field of some –0.3 kA/m [state (e)] the blocking collapses, giving room to a regular domain pattern, which is modified by domain wall motion [image (f)]. The only obvious difference to the previous case is the increasing density of the transverse magnetization modulation, i.e. the concertina pattern becomes finer and occupies more area relative to the area of the entire element.

Dynamic switching

Figure 3.12 contains images of the dynamic reversal. The images reveal a tendency to build up a ripple structure both on the rising [state (b)] and falling edges [states (c) and (d)]. In the latter case the concertina state is pronounced stronger. The reversal begins with an inhomogeneous rotation [state (a)], which is dominated by an interplay between external field and local demagnetizing fields. The same statement remains true for the

![Image](image-url)

Fig. 3.12 (a)-(d) dynamic reversal of a 40µm x 10 µm (4:1) element. Upper row: longitudinal sensitivity images; middle row: transverse sensitivity images; bottom row: schematic interpretation; (e) Kerr signal vs. time with waveform overlay.
trailing edge. The strong horizontal demagnetizing factor slows the rotation down significantly, because in order to switch their vertical orientation the magnetic moments have first to overcome an energy barrier as they assume a horizontal orientation during the rotation process. This causes a high stability of the edge domains on the sides of the element, well seen on both edges of the pulse [images (b) and (d)]. Also the high-density concertina domain network strongly contributes to the deceleration, causing the falling edge reversal to be extremely slow [Fig. 3.12 (e)]. The concertina in the 4:1 element is especially fine and demonstrates the highest stability, compared to all previously considered cases [states (c) and (d)]. A direct comparison of the switching speeds of the 4:1 element for different effective fields, like in Figs 3.7 (b) or 3.10 (b), is unfortunately not possible. The reason for this is that with an increase of the bias field the sample does not reach saturation during the positive, 10 ns long pulse. Figure 3.13 presents the dependence of the speed of the sample reaction for different values of bias fields, but the corresponding temporal spans may not be viewed in terms of switching times.

3.5 Discussion on switching peculiarities in differently applied fields and differently shaped elements

In course of the described experimental results it was shown, that there are certain similarities and differences between reversal processes in the quasistatic and dynamic modes. Quasistatic switching is mainly determined by the distribution of effective fields inside the element. This point may successfully be described in terms of penetrating fields [Sch02]. Under the assumption of an absence of induced anisotropy, which is true for the described samples, the effective field inside the element results from an interplay between the externally applied field and fields imposed by demagnetizing effects. The influence of the latter may also be referred to as shape anisotropy. This anisotropy conditions certain differences in the element’s reversal behaviour. For rectangularly shaped elements
with a different aspect ratio the quasistatic reversal processes were shown to be qualitatively similar. The reversal begins by magnetization rotation in the regions, where the effective torque has its maximum value. For rectangularly shaped elements with external field parallel to the edge the switching always begins at the edges, which lay perpendicular to the field direction. For a square element with diagonal field the switching occurs all over the element’s area. Regardless of the element shape the invoked rotation results in a multidomain state, called concertina. This state is characterized by a low mobility and tends to inhibit the magnetization changes, therefore it is also called blocking state. As the external field reaches a certain critical value, the concertina collapses and a multidomain state establishes. The collapse of concertina in narrow elements requires stronger reverting fields, thus the blocking in these elements is more stable. After the development of regular domains the remaining reversal proceeds by domain wall motion, which is quite sensible to changes in the external field.

The dynamic processes are in some parameters similar to the quasistatic ones. The strongest similarity, held for all considered shapes and aspect ratios, pertains the initial magnetization rotation. In all cases the dynamic reversal begins with a rotation initiated at the same sites, as in the quasistatic case. But the further advance of dynamic reversal becomes quite different, as the fast magnetization processes are essentially determined by magnetization precession, which in many cases dominates over domain wall motion or concertina collapse. The most significant difference is the element’s ability to gradually switch in spite of the presence of a blocking state. The blocking never collapses, but is slowly «melting» as the element is getting closer to saturation. This unambiguously indicates that rotation processes dominate in the dynamic modes. It was also shown that the development of a blocking state is responsible for a deceleration of the reversal.

The shape of the elements also plays a very important role in determining the switching behaviour. Some results that provide a comprehensive overview of the shape’s influence are summarized in Fig. 3.14. The elements with 1:1 aspect ratio (for both diagonal and vertical fields) and with 3:2 aspect ratio demonstrate very close values of the switching times, especially on the rising edge of the pulse, with a strong driving field of 6.3 kA/m [Fig. 3.14 (a)]. Here the switching happens in the sub nanosecond range. On the falling edge the switching requires several nanoseconds, but still
remains well comparable for the three listed elements. This generally demonstrates the evident dependence of the switching time on the driving field strength. For the 4:1 element however the switching times on both rising and falling edges are significantly longer. On the rising edge the switching lasts 2 ns, and on the falling edge roughly 13 ns. This result is due to the different demagnetizing factors and thus demagnetizing fields within the element. The 4:1 element has to overcome significantly higher demagnetizing fields in order to switch as compared to the 1:1 and 3:2 ones. This result remains true also for the quasistatic process as shown in Fig. 3.14 (b), where the magnetization curves of the elements are shown. It is clearly seen, that, as the field is reverted from 2.5 to –2.5 kA/m, the switching of the 4:1 element begins significantly later in terms of the strength of the applied external field. At the same the density of the magnetization rippling in this element has been the strongest for both dynamic and quasistatic cases. This cross-talks to the already drawn conclusion of the decelerating influence of the concertina-like patterns.

Both dynamic and quasistatic switching involve formation of the domain walls. However, the domain walls, which separate the dynamically switched and non-switched areas, are not as sharp and clear cut as those occurring during the quasistatic processes. They rather have a “fuzzy” appearance. Figure 3.15 suggests a schematic model for such a domain wall structure. This model strongly resembles the structure of a cross tie wall, where a low angle magnetization modulation is preferred over straight
180° boundaries based on the energy minimization principle [Hub98]. This structure naturally develops from a concertina state, as different areas of the element acquire different magnetization directions. The resulting multidomain state is very stable and robust against the displacements. The preferred way to introduce changes to this state is incoherent magnetization rotation, whose speed is entirely determined by effective torques. This results in the redistribution of switched and non-switched areas and thus in an effective motion of the fuzzy domain walls. Such incoherent rotation is not necessarily energetically favourable from the quasistatic point of view, because it often results in uncompensated stray-fields, as shown by Schneider et. al. [Sch04, Sch05].

Conclusions.

- Quasistatic domain evolution is modified by shape anisotropy. The switching of the elements from one saturated state into the opposite always begins with magnetization rotation in the regions, where the effective torque is strongest. This rotation further develops into an immobile concertina state (blocking state). After the collapse of the blocking state regular domains appear, and the switching proceeds by domain wall motion.

- Narrower elements exhibit a stronger stability of the blocking state. Such behaviour is based on stronger demagnetizing fields that the element must first overcome.

- Dynamic reversals at their early stages are very similar to the quasistatic ones. They also begin with magnetization rotations that strongly resemble those that arise during the quasistatic processes. These rotations also grow into concertina states that resemble the quasistatic ones and inhibit the further switching.

- The further progress of the dynamic switching is strongly different from the quasistatic one. The concertinas are gradually resolved as the elements continuously switch, demonstrating no sharp collapse. The elements do not demonstrate sharp and well defined domains as in the quasistatic case. The entire dynamic switching is dominated by the incoherent magnetization...
rotation.

- The switching speeds depend strongly on the shape of the element. Narrow elements exhibit much slower switching caused by much more stable blocking states, and stronger demagnetizing fields that must be overcome.

- The strength of the driving field affects the switching speed in a self-evident way. Stronger driving fields cause faster switching since the effective torque is directly proportional to the strength of the applied field.
4. High frequency behaviour of a micro inductor

The increasing frequencies of modern electronic applications set a necessary condition of size reduction of integrated circuits. Inductive elements, whose inductance is a function of geometry only, can definitely not successfully follow this requirement. The reduction of the inductor size will inevitably reduce its inductance, hence its impedance and quality factor. In order to obtain a desired impedance one has to strongly compromise on space on a die, which in turn automatically leverages the associated production costs. For this reason the circuit designers are very reluctant about using inductive coils in their integrated circuits. Up to now the inductors for microelectronic applications have been used in form of spiral-shaped metallic conductors without magnetic cores.

Driven by the desire to optimize the performance of micro inductors, several new solutions have been proposed, which are based on incorporating magnetic materials into inductor design. There are some approaches based on the use of low-frequency materials [Par99, Yam99]. The suggested inductors can work within a range of some hundreds of Megahertz. The use of amorphous materials in inductors allows to shift the working range into the RF band [Fes93], which is of a much greater interest for modern IC’s. Besides the type of used material a wide variety of different designs has also been offered. There are designs, in which the core is surrounded by a wire [Wet01], or a strip-design [Gro99]. These solutions have not offered a significant increase in performance, because of inefficient flux paths within the device. For further increase in inductance the flux path inside inductors can be optimized by aligning it along the hard axis of the induced anisotropy [Web91]. This strongly decreases the influence of eddy currents and associated losses and thus increased the inductor performance. Crawford et. al. [Cra02, Cra04] suggest an additional structuring of magnetic layers into small elements. Such structuring further reduces eddy current losses and also introduces a shape anisotropy into the magnetic behaviour of the device. The array of structured thin film elements possesses magnetic domains, whose behaviour is directly coupled to the electric properties of the inductor.

4.1 Purposes and objectives of the study and sample description.

This chapter describes the results of studies performed on a micro inductor, similar to those introduced by
Crawford et al. [Cra02]. The picture of a part of the inductor is shown in Fig. 4.1. The inductor is realized on a Si/SiO$_2$ substrate. It consists of a 1 µm thick planar Aluminum coil with 200 nm thick Tb-doped Co$_{80}$Ta$_2$Zr$_5$ amorphous magnetic layers on top and underneath. These layers are patterned into rectangular elements. The width of these elements is 28 µm (it is not homogeneous over all the inductor area, but the microscopic studies concentrate on the area with that element size). The Al conductor is isolated from the magnetic media on both sides by 1 µm thick SiO$_2$ layers. The magnetic elements possess a considerable induced magnetic anisotropy, aligned in the same direction in the entire inductor. Besides this, the shape anisotropy also plays a considerable role in their magnetic behaviour. The contribution of these anisotropies leads to a well defined domain structure inside the elements with domain walls oriented along the effective anisotropy direction. The magnetic excitation, exercised on the elements during the inductor’s operation, is strongly different for different types of elements. For those elements, whose anisotropy axis lays parallel (or nearly parallel) to the conductor, the initial magnetic torque, produced by the dynamic field, is very strong, as this field is applied perpendicular to the magnetization direction, thus yielding a maximum value to the cross product of magnetization and field vector. For those elements, whose anisotropy axis is
perpendicular to the conductor direction, the torque produced by the dynamic fields is rather weak. This difference in the acting torque is expected to cause certain differences in the electric behaviour of the inductor.

In this chapter microscopic studies on the magnetic core elements of the inductor are presented and related to its electric properties. This yields information on peculiarities of the domain structure behaviour and their influence on the inductor’s performance. The important initial knowledge about the sample is drawn from quasistatic studies of the reversal processes. They unveil the basic properties of the domain structure, the domain wall motion and the role of the induced anisotropy during the reversal. These studies are performed for external fields applied parallel and perpendicular to the anisotropy direction. At the next step the behaviour of the inductor in pulsed fields is considered. These studies deliver a good and practically important notion about the speed of magnetization processes in a given sample. From a scientific point of view these experiments are also very valuable, since they provide a possibility to simultaneously excite and image reversal processes in elements with different easy axis orientations (relative to the applied field). Such experiments make it possible to pin-point the influence of the induced magnetic anisotropy on the switching properties. The further study focuses on the behaviour of the inductor in harmonic oscillating fields of different frequencies (in its normal functional mode). Such studies unveil some additional peculiarities of the domain behaviour and, most important, provide the possibility to estimate the frequency dependence of the domain wall mobility.

4.2 Inductor in slowly changing magnetic fields

Field applied parallel to the easy axis

Figure 4.2 (a) contains images of the reversal process in external field applied parallel to the anisotropy direction. The field has been reversed from –6.9 kA/m to 5.5 kA/m, as the images of the switching were acquired. The inductor contains many separate magnetic elements, all displaying a similar behaviour. However, it will be helpful not to consider every element seen in the image, but instead to concentrate the attention on just two characteristic elements. One element, described as El 1 [Fig.4.1 (b)] has the easy axis parallel, and the other one (El 2) perpendicular to the conductor. Such choice facilitates
the comparison of the processes at different field orientations or different frequencies and makes it easier to pinpoint the corresponding differences. Both elements have demonstrated a good repeatability of the switching events both quasistatically and dynamically. El 1 is a 28 µm x 32 µm rectangle and El 2 is a 28 µm x 28 µm square. Figure 4.2 (b) also contains an interpretation of the zero field domain states in two representative elements.

The sample was first saturated by a negative field of –24 kA/m, applied by external coils. At –6.9 kA/m the elements are still saturated [Fig. 4.2 (a)]. As the field is reduced to –3.4 kA/m the first black domains, magnetized upwards, appear. In the case of El 1 a black domain appears in the middle of the element and immediately assumes an orientation parallel to the easy anisotropy axis. In El 2 these domains nucleate at
the edge of the element, but nevertheless demonstrate a clear tendency to assume the same orientation. At H = -1.4 kA/m the nucleated domains have grown in size in both elements and retain a perfect alignment to the easy axis. At this stage closure domains are present, they are well seen in the images with both, longitudinal and transverse sensitivities. Thus, the elements follow the Landau model of closed flux domain structures. At zero field the areas occupied by positively and negatively magnetized domains become equal, which corresponds to zero remanent magnetization. The dynamic studies in harmonic fields, following in section 4.5, are based on an excitation of this remanent state by small-amplitude fields. Picture (b) shows an enlarged scheme of the zero-field domains. At further increase of the field the negatively magnetized domains further diminish in size (1.4 and 2.8 kA/m) and finally disappear (5.5 kA/m). Figure 4.2 (c) presents the hysteresis loop for El 2, measured optically by estimating the Kerr signal intensity inside the element. The electric behaviour of the inductor is mainly determined by the magnetization component parallel to the conductor field. The measured loop is almost closed and also shows, that most of the switching process in the field parallel to the easy axis is dominated by domain wall motion (steep onset of magnetization). The slope of the curve is additionally reduced by demagnetizing fields. At high negative and positive field values, where the sample is expected to have reached its saturation, the curve still possesses a non-zero slope. This fact is attributed to a small distortion of the optical measurement, caused by the Faraday effect in the objective lenses and not to any additional change of magnetization. The transverse image at 5.5 kA/m shows some edge domains at the top and bottom of the elements. The magnetization is obviously still unable to completely overcome the local demagnetizing fields in those regions.

Field applied perpendicular to the easy axis

Information about the hard axis magnetization process is collected in Fig. 4.3. The reversal begins with a slight magnetization rotation at the left and right edges of the elements at H = -9.6 kA/m, as follows from the images with vertical sensitivity (transverse to applied field). At H = -4.8 kA/m the rotation has increased to such extent, that a concertina pattern appears in the elements, which again follows from the images with transverse sensitivity. The images obtained with longitudinal sensitivity display first signs of magnetization rotation. At H = -2.9 kA/m this rippling has gradually transformed into a well structured domain pattern with narrow domains, oriented along the easy axis. This pattern is stable at zero field. Figure 4.3 (b) again shows the schematic domain interpretation of the remanent state. Basically, the domains
in this state are very similar to the domains observed in the easy-axis field. The only difference is that the period of the domain structure is now smaller, leaving five longitudinal domains in El 1 and six in El 2 (as compared to three longitudinal domains per element in the previous case). Instead of breaking up into domains parallel and antiparallel to the field direction, the sample prefers domains parallel to the anisotropy direction. This fact reflects the influence of the induced anisotropy during the reversal. On increasing the reversed external field the domains gradually disappear by means of domain wall motion (in Fig. 4.3 (a) fields from 0 to 9.6 kA/m). For the fields higher than 9.6 kA/m only some edge curling (seen at 9.6 kA/m) remains. This curling is removed at higher fields by magnetization rotation. The major part of the element switching takes place in the field range between −10 kA/m and 10 kA/m. This fact is also reflected in the hysteresis curve of El 1, measured parallel to the applied field [Fig. 4.3 (c)]. The segment of the magnetization
curve where the switching occurs (-10 kA/m to 10 kA/m) has the highest slope. At higher fields, both positive and negative, the curve still has a considerable slope which is caused by parasitic Faraday effect rather than by further magnetization processes in the element.

From the results of quasistatic observations in fields along and transversal to the easy axis, it follows, that in both cases a clear domain nucleation and domain wall motion take place. The domain behaviour is dominated by the induced anisotropy. The sample reaches its saturation at \( H = 5.5 \) kA/m for the field applied along the easy axis and at \( H = 10 \) kA/m for transversal field orientation. In the last case some additional magnetization rotation is observed after the domains are cast away, but this rotation takes place at rather high fields (10 kA/m and higher), thus producing no influence during the dynamic studies at lower fields.

4.3 Inductor in pulsed magnetic field

Experiment details

The experiment with the pulsed magnetic field is basically the same as the one performed on the permalloy elements. Therefore the same experimental setup was used. The inductor was embedded into the same sample carrier that was used for the strip-line-based sample from the previous chapter. Nevertheless, the inductor has a strongly different geometry as compared to the strip-line. This results in a need for using long bonding wires to contact the sample to the carrier. This in turn results in some additional disturbances in the line at high frequencies, causing an increasing rise time of the driving pulse to 500 ps. It will be shown, however, that the magnetic reaction of the sample is slow, therefore this increase of the rise time cannot be considered as a critical change.

The inductor consists of 28 µm wide conductors, and all elements have dimensions in this range. The thickness of the elements is 0.2 µm. Applying an expression from Aharoni [Aha98] to estimate the demagnetizing self energy, yields the conclusion, that the effective out-of-plane demagnetizing factor equals 0.974. This again means that most of the magnetic processes are confined to the plane of the elements. The out-of-plane components that are expected to appear during magnetization precession, have a very small
amplitude and are invisible in the experiment. Therefore, their contribution to the entire magnetization vector is also very small. For this reason it is most relevant to consider the in-plane fields, produced by the inductor coil. Applying expression (2.7) to estimate the strength of the longitudinal field component, delivers a value of 0.355 kA/mV. With 40 V pulse amplitude a pulsed field of 14.2 kA/m is obtained. This field exceeds the saturation field in both directions parallel and perpendicular to the easy axis. Figure 4.4 (c) contains a plot of the waveform in grey.

Unlike in the case of the permalloy elements the background reference image is obtained not in an externally applied field, but at the point, where the pulse reaches its maximum (shown on the waveform in Fig. 4.4 (c)). This is done with purpose to re-ensure, that the observed magnetic images contain information produced by pulse excitations only. The temporary application of an external negative field may result in an undesired modification of the remanent state, not related to dynamic phenomena. In case of the permalloy elements the background images had been taken at the negative saturation of the sample in the external field before the pulse excitation arrived, and not at the remanent state.

**Dynamic behaviour of the elements**

Figure 4.4 (a) contains a set of images with Kerr sensitivity parallel to the anisotropy direction, along which the domains are oriented. Figure 4.4 (b) schematically shows the pulse field acting on the elements. The same waveform with the same field strength is simultaneously acting on two different groups of elements, whose anisotropy directions are either perpendicular (El 1) or parallel (El 2) to the applied field. Figure 4.4 (c) contains the plot of the waveform together with Kerr signal plots of the corresponding elements, and 4.4 (d) contains a schematic interpretation of the most important stages of the switching process (I through V). At the time point of -2.3 ns the sample is in its remanent state. This situation corresponds to stage I in picture (d). The domains, whose magnetization is either parallel or antiparallel to the anisotropy direction, are shown.

The domain state of El 1 is practically the same as the remanent domain state in this element during the hard axis quasistatic reversal (see Fig. 4.3). The pattern consists of 5 domains, oriented parallel to the easy axis. The state of El 2 is almost similar to the remanent state of this element during the easy axis quasistatic
reversal (Fig. 4.2), with the exception, that in the pulsed field an additional small domain appeared on its right edge. Both elements also possess similar closure domains at the top and bottom edges. The contrast in the presented images is inverse relative to that of the quasistatic series. Altogether similar basic ground-state domain patterns for both quasistatic and dynamic processes are observed.

Fig. 4.4 Dynamic behaviour of the inductor in the pulsed field. (a) series of difference microscopic images obtained during the pulsed excitation of the inductor elements. The reference image is captured at 9.9 ns, where the element 2 (El 2) is in the single domain state with possibly slight deviations of the magnetic moments from the uniform orientation; the magnetization in element 1 (El 1) is strongly rotated towards the field direction (to the right on the presented images). (b) shows the schematic view of the selected elements and field geometry. (c) shows the Kerr signal plots for both elements with field waveform overlay. (d) shows the schematic interpretation of the observed switching stages. State I corresponds to the initial remanent state. State II shows the begin of rotation processes on the rising edge. State III shows the state, at which the reference images are acquired. Magnetization in El 1 is strongly rotated, but domains and walls are not destroyed; the walls are shown as dashed lines. State IV shows the re-nucleation of domains and rotational processes on the trailing edge. State V is basically same as I.
At the time point of 0.8 ns the pulse has arrived with a field strength of 11.8 kA/m, which is practically the double strength of the saturation field for El 2 and which also exceeds the saturation field for El 1 (compare to hysteresis curves in the previous section [Fig. 4.2 (c) and Fig. 4.3 (c)]). A decrease in the contrast inside the elements is noticeable, as the magnetization rotates back to its reference value, but nevertheless one does not notice a sign of domain wall motion. Some 0.9 ns later, at the time point of 1.7 ns the contrast inside the elements is rather weak, but it is still possible to distinguish between brighter and darker regions, which used to be the initial domains in the remanent state. In the schematic diagram (d) this corresponds to state II. Hence, it can be concluded, that during the high-speed excitation domain wall motion in this sample does not participate in the switching of the elements; magnetization rotation dominates. The domination of magnetization rotation was as well the case for the permalloy elements, but for the inductor this phenomenon is emphasized much stronger. Another point to notice is the speed of the rising edge switching. Both elements display almost equal and simultaneous changes in the Kerr signal, and both of them are not fast enough to follow the sharp rising edge of the waveform.

The time point of 8.9 ns corresponds to the reference state of the elements, thus no optical information is contained in the corresponding image. On the schematic diagram this situation corresponds to state III. Element El 2 is almost saturated by the pulse field, aligned along its easy axis, and its magnetization points mainly downwards with slight deviations, as indicated on the schematic interpretation [Fig. 4.4 (d) state III]. No domains are contained in this state. The mentioned deviations are not directly visible or measured, they are rather expected to be present, because a perfect magnetization alignment with the applied field usually takes longer times. Element El 1 at the time point of 8.9 ns was not saturated by the field of 14 kA/m, although this field exceeds the quasistatic saturation field value by almost 50%. The magnetization in this element is strongly rotated to the right by the hard axis pulse field, yet the domains and domain walls could not be destroyed. These domains and walls are not visible on the difference image, and in the diagram they are shown by a dashed line. At 10.7 ns (corresponds to state IV on the diagram), right on the trailing edge of the pulse, the immediate appearance of domains in El 1 is observed, however in the El 2 the domains are still absent. If the element 1 had been saturated, then the domains would have been unable to appear that rapidly. There is another important peculiarity to notice in El 1 at the time points of 10.7 and 11.9 ns: the domains, which have just become visible, have slightly changed their orientation. Previously the domains are tilted to the left, according to the anisotropy direction, but now they are aligned vertically.
The first signs of contrast in El 2 appear at 14.7 ns, about 4.7 ns after the trailing edge of the pulse, corresponding to state IV in the schematic diagram [Fig. 4.4 (d)]. At this state the black domain in the center of El 1 becomes well visible, whereas the other domains are only vaguely seen, their boundaries are therefore shown by dashed lines. At time steps of 21.7, 31.7 and 41.7 ns all domains in El 1 appear, and their orientation is slowly rotating from straight vertical to left-tilted (along the easy axis). Thus a combination of magnetization rotation and domain wall motion takes place. A fast rotation process is responsible for the domain appearance, and slow domain wall motion gradually aligns the appeared domains along the most favourable direction. In case of El 2 the situation is somewhat different. Here the domains appear by means of rotation only, and assume the favourable left-tilted orientation from the very beginning. This process develops further, and at the time point of 59.7 ns the domain state is equivalent to the initial remanent state (stage V in the schematic diagram). The vague appearance of domains could be a sign of a certain irreproducibility of the reversal processes in the element. This irreproducibility, however, can only reduce the quality of the image, but does not affect the integral Kerr signal measurements. The Kerr plots clearly show, that the magnetization in El 2 requires more time to reach the initial state than in El 1. This is due to the fact, that the 10 ns pulse was not able to saturate the El 1. The magnetization is strongly tilted to the right, along the field direction and against the easy axis direction. Nevertheless, the domain walls (although modified) are still present, and after the fall of the pulse the element “knows” to which state it is supposed to relax. The relaxation takes place as a fast rotation, combined with slow domain wall direction adjustment. At the same time the pulse field applied to El 2 along the easy axis has destroyed the initial state information, and the element has to find its way back to the energy minimum by means of rotation. This process is much slower, but the newly formed domains immediately assume the most favourable position and do not show unnecessary motion.

**Summary on inductor’s dynamic behaviour in pulsed field**

The inductor basically consists of two groups of elements, to which the field of the coils is applied either parallel or perpendicular to the easy direction. The element with the anisotropy direction aligned parallel to the coil field can be saturated by the 14 kA/m field pulse, whereas an element with perpendicular orientation cannot. The relaxation of the elements in stray and anisotropy fields is also considerably different. All fast magnetization modulations (on the rising edge) have occurred by magnetization rotation only. The slow
processes (during relaxation) occur predominantly by magnetization rotation, but also by slight domain wall motion.

In conclusion, the two groups of elements possess a different speed and different extent of magnetization modulation during the excitation in strong pulsed fields and relaxation in moderate anisotropy and demagnetizing fields. This may play an important role during the inductor’s operation, leading to different phases of the inductive response produced by the different groups of elements.

4.4 Microscopic studies under harmonic excitation

In the previous section it has been shown, that under pulse excitation different magnetic elements of the inductor demonstrate different response speeds. The main reason for this difference are different effective torques acting on the elements. In this chapter the behaviour of the inductor in harmonic oscillating fields is studied. This study directly leverages the ability of the used setup to perform the time resolved imaging at arbitrary frequencies, which is not offered by any other imaging method.

Experimental details

The experiments were performed following the same basic layout as described before except for using a cosine waveform generator instead of the pulse generator. A set of studies was done for frequencies of 50, 80, 100, 200, and 500 MHz. The excitation amplitude was kept constant for all cases. With a wave amplitude of 8.1 V the corresponding peak-to-peak dynamic in-plane field amplitude equals 2.9 kA/m. This in turn means, that the sample is symmetrically excited in both, negative and positive, directions with a field of 1.45 kA/m. Shown are difference images only, which just show the change of magnetization relative to a fixed reference state and not the true domain states as before. The excitation of the sample is continuous and uninterrupted so that the sample does not have time to relax to any specific state. The reference images are always captured at zero-delay time. Neither absolute field values nor domain states in the reference images are known (it is clear however that the domains are oscillating around their zero-field position). The obtained data still contains the essential information about the temporal magnetization behaviour and the magnetization speed difference between two different groups of elements. The necessity
of this method is dictated by the very weak signal, produced by the inductor at such low excitations.

**Elements under 50 MHz excitation**

Figure 4.5 (a) contains images of the inductor elements, excited by a 50 MHz wave. This frequency corresponds to an excitation period of 20 ns. Images with both, vertical and horizontal sensitivity directions are presented. The zero-time image is by itself the reference image and thus contains no magnetic contrast. At 2 ns in the images with vertical sensitivity first slight changes in the magnetization states in both kinds of elements become visible. The elements with easy axis aligned perpendicular to the field become darker in the image with horizontal sensitivity. At the time point of 4 ns a clear cut domain contrast in both groups of elements is observed. The images reveal just the deviation of the magnetization from the reference domain state at zero-time. Sharp stripes aligned along the anisotropy direction unambiguously indicate, that both groups of elements demonstrate domain wall motion. Nevertheless, there is some difference in the behaviour of El 1 and El 2. For El 2 it is only possible to see the appearance of black stripes that reflect the displacement of the domain boundaries, whereas in El 1 additionally the entire contrast of the element becomes darker in the image with horizontal sensitivity. This means that in El 1 the domain wall motion is simultaneously accompanied by magnetization rotation. At 6 ns the qualitative picture of the process remains the same, but the contrast becomes somewhat stronger and sharper. At 8 ns the dark stripes remain the same as before, but the background contrast (i.e. magnetization rotation) in El 1 is less pronounced. At 10 ns only wall contrast remains in all elements, indicating the absence of rotation. All through the remaining time steps the wall displacement contrast slowly disappears as the walls gradually assume their initial position. At 14, 16, and 18 ns the horizontal contrast in El 1 becomes bright, as the external field has reverted its direction. The final state at 20 ns (not shown) corresponds precisely to that at 0 ns.

These observations demonstrate that at 50 MHz both types of elements reveal a noticeable domain wall motion. In addition the elements with the easy axis oriented perpendicular to the applied field show magnetization rotation. These phenomena have a straightforward explanation, which is yet based on quasistatic considerations. First of all, the 50 MHz frequency is not yet fast enough to hinder the domain walls in both elements from following the excitation. In El 2 the domain state changes in such a way, that domains magnetized parallel to the field grow at the expense of the antiparallel domains. This occurs by
domain wall motion and no magnetization rotation is necessary. In El 1 the field is applied almost perpendicular to the magnetization direction, exercising a maximum torque and thus causing rotation in addition to domain wall motion.

Another difference in the behaviour of the two types of elements emerges from considering the Kerr signal...
plots of two elements in Fig. 4.5 (b). In this plot the magnetization components along the direction of the applied field are presented. These components are most important from the point of view of electrical performance of the inductor. They are obtained by estimating the Kerr images with horizontal sensitivity for El 1 and vertical sensitivity for El 2. The elements follow the excitation so that their responses are slightly phase-shifted relative to each other. The correlation analysis delivers a time shift of 1.5 ns, which corresponds to a phase shift of 27°. This in turn means that at the frequency of 50 MHz the corresponding components demonstrate rather close reaction speeds, despite the differences in the effective torque.

Summarizing the behaviour of the two elements at 50 MHz, the following conclusions may be drawn: both elements display a considerable domain wall motion. Nevertheless, in El 1 it is magnetization rotation that will be responsible for the electric performance of the element. Both magnetization components that are expected to produce the major influence on the inductive signal possess nearly equal phases, and thus reaction speeds.

**Elements under 100 MHz excitation**

The data on the dynamic behaviour of the inductor at 100 MHz are summarized in Fig. 4.6. The same set of data as before is represented. The zero time image is again the reference image and contains no optical information. After 2 nanoseconds a clear contrast in both groups of elements in the image with vertical sensitivity is observed. The image with horizontal sensitivity contains contrast only for the elements with perpendicularly oriented easy axis, which again denotes magnetization rotation.

The domain wall motion in case of the 50 MHz excitation has produced black stripes in the difference images, whereas in this case the corresponding stripes are white. The reason for this is that the reference images for different frequencies are obtained at different phases of the process. Unfortunately it is not possible to determine at which phase of the waveform the reference image is acquired. This results in an arbitrary choice of the reference point for different frequencies, and thus in different optical appearances of magnetization changes. It is also open how much the corresponding changes are delayed relative to the waveform. But nevertheless the relative delays between the different elements may be derived, and thus the corresponding differences in their reaction speeds. The differences in the contrast appearances are
At 3 and 3.5 ns the vertical contrast increases in both groups of elements. For El 1 also the horizontal contrast increases as the rotation proceeds. At 4 ns a decrease of vertical contrast in El 2, and a further increase of rotational contrast in El 1 are noticed. This means, that a certain de-phasing between the
responses of the elements is being observed. At 5 ns the vertical contrast of El 2 begins to reverse from bright to dark, whereas the dark horizontal contrast of El 1 reaches its maximum. The remaining images show a gradual transition of the sample back to its reference state, which is achieved at 10 ns. For a quantitative analysis of the elements’ behaviour again the Kerr signal plots must be considered. The combined plot of the signal components along the field direction, shown in Fig. 4.5 (b), clearly reveals a shift between the Kerr signals of the two elements. The time shift equals 1.5 ns, which corresponds to a phase shift of 54° (exactly one radian). The time shift is the same as in case of the 50 MHz excitation. It is the decreasing oscillation period that boosts the corresponding phase shift.

The main conclusion of this section is, that with increasing frequency the relative phase shift between the responses of the two types of elements also increases. This is a consequence of the fact, that at higher frequencies the elements are less able to follow the external excitation. The signal in El 2 is dominated by domain wall motion, which by itself is known to be slow. The signal of El 1 is dominated by magnetization rotation, which is much faster. Besides that, the effective torque in El 1 is much stronger, as the field acts perpendicularly to the magnetization. Consequently the El 1 shows a better mobility and is by 1.5 ns faster than the El 2. In the quasistatic case the situation was qualitatively different. The elements could be easier modified by the field applied along the easy axis. Thus at 100 MHz the behaviour of the elements begins to strongly deviate from its quasistatic counterpart.

**Elements at 200 MHz excitation**

Figure 4.7 presents the corresponding set of data for excitation with a 200 MHz wave. The excitation period equals in this case 5 ns. At 0.5 ns the first changes in contrast of El 1 in the image with horizontal sensitivity can be seen, which are again caused by magnetization rotation. At 1 ns this rotation becomes more noticeable. First changes in El 2 can be noticed at 1.5 ns, when the horizontal contrast of El 1 begins to disappear. This observation clearly denotes a strong magnetic phase shift between the elements. The wall contrast in El 2 reaches its maximum at about 2.5 ns, whereas the corresponding contrast of El 1 has already inverted (from dark to bright). The remaining images again show the return of the elements into their reference state. During this process the wall contrast in El 2 slowly disappears, as well as rotational contrast in El 1.
For a quantitative estimation the Kerr plots shown in Fig. 4.7 (b) have to be referred to. The plot of the magnetization components, aligned along the exciting field and thus responsible for the electric performance, shows, that the signals are once again shifted by 1.5 ns (exactly as in the cases of 50- and 100 MHz excitations). The corresponding phase shift equals now 108°. Thus, the application of the higher frequency to the inductor has resulted in a further de-phasing of the elements with different anisotropy orientations.

Fig. 4.7 Inductor under the 200 MHz harmonic excitation. (a) difference images of the dynamic magnetization process with the reference taken at zero-delay; (b) Kerr signal plots of the magnetization components along the field direction.
Elements at 500 MHz excitation

The frequency of 500 MHz closes the microscopic studies on the harmonic inductor excitation. The corresponding data are presented in Fig. 4.8. The period of the entire excitation cycle equals now 2 ns. The images with horizontal sensitivity again show a clear magnetization rotation in El 1. The vertical contrast in El 2 is best visible at 1 and 1.5 ns steps. This contrast does not resemble that of mere domain wall motion any more, because the corresponding clear cut stripes that denote the boundary displacement cannot be observed. Instead, the entire domains, which are magnetized against the applied field direction, are changing their contrast (from grey to bright in this case). This is an indication, that domain wall motion is unable to participate in the element’s magnetization change at this frequency. Instead, the element prefers magnetization rotation as the faster way to react to the external excitation. The torque, produced by the field of the coil, is much smaller for El 2, as the field is applied at about 12° relative to magnetization direction, which makes the corresponding $\mathbf{B} \times \mathbf{H}$ product not as large as for El 1, where the field is applied

![Fig. 4.8 (a) difference images of the dynamic process under 500 MHz harmonic excitation; (b) Kerr signal plots for components along the field direction.](image-url)
at 78°. For this reason a delay between the reaction speeds of the two different groups of elements can be noticed, and El 1 remains to be the faster one. A quantitative estimation of the delay between the elements delivers a difference of 0.7 ns, which corresponds to a phase shift of 126°.

**Summary on the inductor’s magnetic behaviour**

- The inductor consists of two groups of elements, whose easy axes and thus remanent magnetizations are oriented either nearly parallel or perpendicular to the magnetic field produced by the coil. This basically results in a different effective torque on the magnetization, produced by the field of the coil.

- The quasistatic reversal processes have been occurring in a predictable and well understood way. With the external field applied along the easy axes of the elements the reversal is mainly achieved by domain wall motion. The remanent state for both groups of elements during such reversal consists of three domains, aligned along the anisotropy direction and connected by closure domains to avoid field leakage [Fig. 4.2 (b)]. During the hard axis reversal both groups of elements demonstrate similar, yet finer domain structures [Fig. 4.3 (b)] in the remanent state, whereas the reversal itself is governed by both rotational processes and domain wall displacement.

- The observations of the inductor’s behaviour in the pulsed field show, that the elements clearly demonstrate different responses to the fast excitation. The El 1 with anisotropy axis almost perpendicular to the pulse field demonstrates a strong magnetization rotation, but still retains the memory about the initial domain structure. The relaxation of this element is mainly achieved by fast magnetization rotation, accompanied by slow re-adjustment of the domain wall angle to the anisotropy direction. The El 2 demonstrates a strongly different response. Its domain structure is completely destroyed by the field pulse, and for this reason the relaxation is very slow, because the magnetization has to newly “seek” its equilibrium state. Such difference in the behaviour of the elements is explained by the mentioned differences in the effective torques.

- The studies of the inductor under harmonic excitation at different frequencies deliver a closer comparison of the reaction speed of different elements. At low frequencies (up to 100 MHz) both elements display
domain wall motion, but El 1, whose easy axis is aligned perpendicular, also displays magnetization rotation. At 50 MHz this rotation is 1.5 ns faster than the domain wall motion in El 2; such time shift does not result in any significant phase shifts between the magnetization components responsible for the electric performance of the inductor. At 100 MHz the time difference retains a value of 1.5 ns, but this in turn means a considerable difference in the phase shift. At 200 MHz this shift further increases. At 500 MHz magnetization rotation begins to prevail in El 2 as well, because domain wall motion cannot follow such a fast excitation. Thus, the performed experiments have also make it possible to establish a range of domain wall mobility (up to 500 MHz for the given sample). Due to the differences in the effective torque acting on El 1 and El 2 the phase shift between the elements is present also at this frequency. Figure 4.9 summarizes these observations by showing the phase and time shifts as a function of applied frequency. The obtained results nicely complement the inductive measurements on thin film samples [Sil99, Neu04].

Fig. 4.9 Time- and phase shifts between El 1 and El 2 plotted vs. frequency.
5. Conclusions

The magnetic dynamic behaviour of micro- and especially nanoparticles should be adequately and completely described by the Landau- Lifshitz (LL) theory, presented in 1935. Yet, the suggested theory is phenomenological. Up to now there is no better and more effective uniform way to address the problem more strictly. Actually some discrepancies, related to calculated and measured energy dissipations, are pinpointed by Baryakhtar and Ivanov [Bar97]. The general validity of the LL equation is thus questioned. But even taking a comprehensive and simplified LL or Landau- Lifshitz- Gilbert (LLG) material equation (equ. 1.6, 1.7 or 1.8) and solving it together with a general micromagnetic equation (1.5) is hindered by a lot of difficulties and uncertainties. They arise from the high complexity of seemingly simple “real-world” objects, such as patterned thin film elements. Defects, stress induced anisotropies, thermal effects, and similar factors can be taken into account during calculations only in an approximate way (see [Ber04] for an example of thermal noise consideration). Such calculations may offer a comprehensive overview of the main tendencies of the dynamic behaviour of the sample, but do not necessarily offer a complete and reliable description. These problems enormously scale up with increasing sample size, where it should also be counted with domain walls and their interactions. For these reasons any experimental study of magnetization processes often delivers a better and more reliable knowledge and refines many features of generally known theoretical aspects. This statement is especially true for dynamic processes.

This work has introduced a new and effective way to study magnetization dynamics. The presented lab setup offers an utmost flexibility in practically all parameters (repetition rate, triggering, excitation type, external field application, quasistatic imaging, etc.), and in this aspect definitely exceeds today’s existing methods and approaches. It seems to be the only way to systematically study all aspects of reversal (optical hysteresis measurements, domain structure transformations, anisotropy distributions, etc.), both dynamic and quasistatic. Other techniques, which offer a better resolution (both spatial and temporal), are mostly suited for performing just a single set of assignments, not offering a wide range of other research possibilities. Some of them are also associated with huge costs in terms of money, facilities and manpower that result in their strictly limited availability. Nevertheless, the suggested method also contains some drawbacks in comparison to other approaches. A certain compromise is made on time resolution, where the 250 ps are offered instead of 20 [Neu05] to 50 ps, typical for laser scanning and
wide-field technique. The obtained spatial resolution of 0.8 µm, is not as high as the potential resolution of PEEM microscopes, for instance, but is nevertheless sufficient to study reversals in elements of about 10 µm size. The hardware required for the time resolved imaging was commercially obtained from LaVision GmbH [LaV]. The integration of the experiment including the development of control and estimation software, sample design, field strength and resolution calculations are performed in the course of this thesis.

The results of extensive studies on differences and similarities between dynamic and quasistatic processes for patterned thin film low-anisotropy elements are presented in this work. It is shown, that the switching from one saturated state into another is initiated in form of magnetization rotation. In both cases this rotation grows into a complicated blocking state, also called concertina. In slowly changing fields this state is resolved by an irreversible collapse into the Landau state. The switching cannot proceed in the presence of a concertina in quasistatic case. After the pulse field excitation the switching takes place with the simultaneous presence of a concertina. This indicates the dominance of incoherent magnetization rotation over domain wall motion. Actually, the presence of concertina during dynamic switching is not new, it has been seen by the group of Mark Freeman few years before [Bal00, Hil02], but no systematic study and explanation has been offered on this issue. The existing knowledge is extended in this thesis and a detailed qualitative explanation for the experimentally observed phenomena is offered.

The domain structures that occur during the dynamic switching are strongly dependent on the geometry of the sample. Rectangular samples demonstrate the presence of the concertina states during the reversal processes. These states however become stronger pronounced and possess greater stabilities with the increasing aspect ratios of the elements. In a similar way the blocking state in the square element with diagonally applied field is better pronounced and more stable than that in the square element with vertical field. These effects have been traced down to the corresponding differences in the local demagnetizing fields near the edges. An increase in the stability of the concertina state inevitably leads to a corresponding decrease of the switching speed.

The microscopic results of chapter 4 have been obtained exclusively due to the unique triggering flexibility of the camera system, which makes it possible to image a high speed harmonic excitation. A transition
case, where the domain wall mobility becomes a function of excitation frequency is experimentally shown. Excited with frequencies up to 100 MHz, a given set of magnetic elements clearly demonstrates a domain structure reordering governed by domain wall motion. Rotational processes are also present, but the contribution of the domain wall motion is pronounced stronger. At a frequency of 200 MHz both domain wall motion and magnetization rotation equally contribute to the modification of the magnetic structure of the elements. At 500 MHz the magnetization processes are dominated by magnetization rotation, showing no well-defined domain wall motion.

Magnetic elements, excited by fields parallel to the induced anisotropy direction, demonstrate slower reaction speeds than those excited by transverse fields. This phenomenon is observed during both harmonic and pulse excitations. It is again explained by the differences in the effective torque acting on magnetic moments. It has been shown, that such difference leads to the de-phasing of the magnetic response of different segments of microinductor’s magnetic core.
List of Sources and References


Ken: www.kentech.co.uk


LaV: www.lavision.de


Author expresses his most sincere thanks to:

- Prof. L. Schultz, Dr. R. Schäfer, Dr. J. McCord

- Prof. C. M. Schneider, Priv. Doz. J. Fassbender, Dr. I. Mönch, R. Kaltofen, Dr. H. Vinzelberg, S. Schinnerling, Dr. H. Siegel, Dr. R. Kunze, Dr. A. Crawford, Prof. S. Wang

- Dr. O. deHaas, A. Neudert, S. Flohrer

- Dr. H. Geisler, Dr. E. Zschech, Dr. M. Hecker, Dr. H. J. Engelmann

- Fakultät Maschinenwesen der TU-Dresden