PROJECT FINAL REPORT

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UltraMagnetron

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Ultrafast All-Optical Magnetization Reversal for Magnetic Recording and Laser-Controlled Spintronics

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(Theme 4 – NMP - Nanosciences, Nanotechnologies, Materials and new Production Technologies)

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1. Final publishable summary report

1.1 An executive summary

The aim of the proposed research was to develop "opto-nano-magnetism" that is, the manipulation of the magnetic properties of nanomagnetic materials using (magneto-) optical effects, as a novel approach for future magnetic recording and information processing technology. This topic is situated at the junction of coherent nonlinear optics, nanophotonics and magnetism. In particular, we investigated the effects of light on magnetic order at the nanoscale, optimize materials and conditions for highly efficient and ultrafast (10^{-12} seconds and faster) optical control of nanomagnets and in this way tried to initiate a development of novel technology for unprecedented fast (THz) magnetic recording and information processing.

The project had the following objectives

- **obtain fundamental knowledge on ultrafast opto-nano-magnetism and ultrafast magnetization dynamics at the nanoscale** (understanding laser-induced magnetization reversal in nanomagnets smaller than 300 nm).
- **achieve highly efficient nanolocalization of magnetism** (laser-induced magnetization reversal faster than 100 ps and with spatial resolution below 300 nm).
- **develop novel approaches for truly ultrafast femtosecond laser control of nano-magnetism** (switching of nanomagnets faster than 1 ps)
- **initiate developments of novel technologies for unprecedented fast THz magnetic recording and information processing, including spintronics** (developing the conceptual design of ultrafast recording and spintronics devices)

After 36-months performance of the project we have achieved most of the objectives planned. In particular,

- Novel mechanisms and approaches of magnetization reversal at sub-100 ps time-scale in continuous films and structures with size down to 200 nm have been discovered and theoretical understanding has been vastly improved
- Novel approaches for laser control of nanomagnetism at the picosecond time-scale which could not be even predicted before were discovered
- Knowledge accumulated in the project has been transferred to industries. Seagate and Philips have analyzed the future of the opto-magnetic technology in commercial devices suggesting a conceptual design for opto-magnetic read-head and required picosecond laser. NXP sees no product application for spintronic devices in their future development because of strategic changes in the company. All-optical switching has made it to the roadmap of the HDD industry, as the next technology after HAMR. The consequence would be that a production of 400 million lasers each quarter to be incorporated in write heads. According to an analysis of Philips, this is potentially doable.

1.2 A summary description of project context and objectives

During the last decades the operation speed of computers has grown exponentially, while chip dimensions decreased, bringing the clock speed into the GHz range. However, the speed of magnetic storage of data and processing magnetically stored information, as on a hard disc or in Magnetic Random Access Memory (MRAM), is presently limited to a few nanoseconds. Moreover, based on current technology of magnetization reversal the operation speed of these spintronic devices is approaching its practical limit. Consequently the demand for the ever-increasing speed of information storage and manipulation has triggered an intense search for ways to control the magnetization of a medium by means other than magnetic fields. The control of magnetism by light is one of the promising approaches to this problem, since a laser pulse is one of the shortest ever man-made events.

There is no doubt that recent progress in the development of compact ultrafast lasers, the successful introduction of lasers into magnetic storage technology as well as enormous breakthrough in the understanding of spin-dependent phenomena in solids will further spur the realization of ultrafast magnetization reversal in storage and spintronics devices. Nevertheless, there are still many fundamentally intriguing issues to be answered on the way to real applications of opto-magnetic phenomena and a "THz opto-magnetic revolution" in magnetic recording and information processing. Particularly,

- Laser control of magnets with sizes smaller than the wavelength of light raises many intriguing questions at the junction of nano-photonics, magneto-optics and nano-magnetism. Future magnetic recording bits should be at most 300nm*300nm. How will light interact with spins in such nano-magnets and what will be the distribution of the laser-induced magnetic field at the nanoscale?

- The excitation with femtosecond laser pulses puts a medium in a highly non-equilibrium state, where a conventional description of magnetic phenomena in terms of thermodynamics is no longer valid. Therefore the phenomenon of ultrafast magnetization reversal is poorly understood.

- Technology and design of materials and nanostructures for faster magnetic recording as well as for ultrafast programming of spintronics devices must be developed, which can only be done by combining forces in material fabrication, nano-structuring, micromagnetic simulations, nanoprobing of magnetism and ultrafast magnetization dynamics.

Objectives of the project

In order to address these fundamental issues we have formulated the following objectives:

- **obtain fundamental knowledge on ultrafast opto-nano-magnetism and ultrafast magnetization dynamics at the nanoscale** (understanding laser-induced magnetization reversal in nanomagnets smaller than 300 nm).
- **achieve highly efficient nanolocalization of magnetism** (laser-induced magnetization reversal faster than 100 ps and with spatial resolution below 300 m).
- **develop novel approaches for truly ultrafast femtosecond laser control of nano-magnetism** (switching of nanomagnets faster than 1 ps)
- **initiate developments of novel technologies for unprecedented fast THz magnetic recording and information processing, including spintronics** (developing the conceptual design of ultrafast recording and spintronics devices)

To address these fundamental and practical problems we have formed a multidisciplinary consortium of academic and industrial partners with complementary expertise in coherent nonlinear magneto-optics and ultrafast magnetization dynamics (P1, P5), spatially and time resolved magnetooptics (P6, P1), nanophotonics and X-ray nanoprobing of magnetism (P5, P4), atomistic simulations of subpicosecond magnetization dynamics for strongly nonequilibrium ensembles of spins (P2, P9), technology of magnetic nanostructures (P3, P6), including those based on novel magnetic diluted semiconductors and half metals (P6) and their applications in spintronics. In addition we have formed a user-group from high tech companies, both large and small that will monitor and assess the scientific progress (P3, P7, P8).

Progress beyond the state-of-the-art

Nanoscale magnetic switching and its dynamics, although presently poorly understood, are the central issues for the magnetic recording and information processing technologies as the size of the recorded bit shrinks to the nanometer scale and the data retrieval rate increases. Though bringing the densities to the next level of Tbit/inch^2 appears to be feasible, implying bit size 30 nm × 120 nm, the speed of recording and processing of magnetic information is facing a fundamental and technological gap. A similar problem is experienced by the recently emerged spintronics-technology and Magnetic Random Access Memory (MRAM) devices, in particular (see Fig. 1.1).

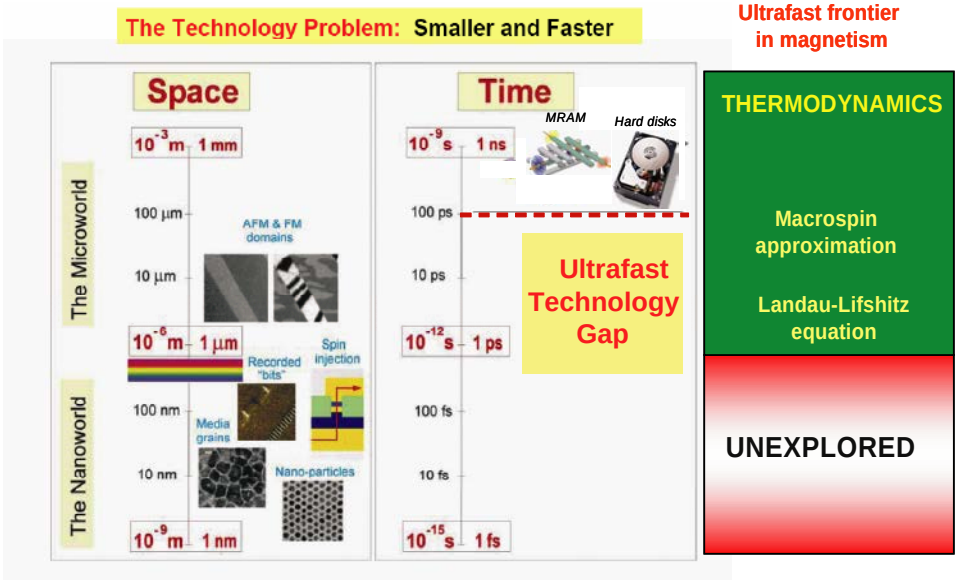

Fig. 1.1. Ultrafast frontier in science and technology gap (inspired by J. Stöhr, and H.C. Siegmann, Magnetism: from Fundamentals to Nanoscale Dynamics (Springer, Berlin, 2006)) .

Although MRAM possesses very strong advantages over its alternatives (Dynamical RAM and Static RAM), such as being non-volatile and relatively fast, the state-of-the art speed for manipulating magnetic bits in spintronics is lagging far behind the clock in modern processors. The understanding of fundamental and practical limits of the

speed of manipulation of magnetic bits and spins of electrons is therefore of vital importance for further development of these future technologies.

The conventional way to reverse the magnetization **M** is to apply a magnetic field **H** antiparallel to **M**. Much faster magnetization reversal can be obtained if the magnetic field is applied perpendicularly to **M**. In this case the magnetization starts to precess around the direction of the magnetic field **H**, as described by the Landau-Lifshitz equation. If a strong enough magnetic field is applied during only a half period of the precession, switching of the magnetization occurs. In ferro- and ferrimagnetic materials, the period of precession and thus the switching speed, is approximately a linear function of the external magnetic field. One would thus expect that the speed of such switching can in principle be increased infinitely and only be limited by practical conditions, i.e. the necessary field pulses. However, it was recently concluded that deterministic precessional switching of magnetization cannot occur below 2 picoseconds. Beyond this time limit the magnetization was shown to become fractured by the intense magnetic field pulse employed and the switching process became random. Also, the strength and duration of electrically generated magnetic field pulses in practical devices is limited. Thus it has been pointed out that a magnetic field cannot be a stimulus that can be used for ultrafast THz magnetic recording and the search for novel and alternative ways to excite spins and to reverse magnetization at the picosecond time-scale becomes necessary.

Optical pulses could be an alternative stimulus for the manipulation of spins and magnetization. In theory, intense circularly polarized light can influence magnetic systems in a way similar to an external magnetic field parallel to the wave-vector of the light. Moreover, right- and left-handed circularly polarized waves should act as magnetic fields of opposite sign. Recently, our consortium has demonstrated that circularly polarized laser pulses act on the magnetization as a magnetic field pulse up to 1 T. Although it had been previously believed impossible, we succeeded even to reverse the magnetization in a metallic thin film of GdFeCo-alloy by a single 40 femtosecond circularly polarized laser pulse without any applied magnetic field. The direction of such opto-magnetic switching is unambiguously set by the helicity of light. This fact clearly demonstrated the feasibility of both all-optical magnetic recording and ultrafast optical programming of spintronic devices. Can such an all-optical switching operate at the nanoscale? It has been recently demonstrated theoretically as well as experimentally by our consortium that adaptive shaping of the amplitude, phase and polarization of femtosecond laser pulses can indeed be an effective tool for nanoscale localization of ultrafast optical exitation.

In this project we will initiate the development of unprecedented fast (THz) magnetic recording and information processing, including spintronics by combining the expertise of partners in all-optical magnetization reversal, subwavelength localization of optical fields, X-ray nanoprobing of magnetism, atomistic calculations of magnetization reversal as well as state-of –the art technology of metallic and semiconducting magnetic nanostructures.

Overall strategy

To achieve the objectives of the project we are going to use novel “state-of-the-art” approaches in experiment, simulations and technology, including the excitation and observation of magnetism on a femtosecond-time and nanometer-length scales, simulation of magnetization reversal in nanomagnets under strongly nonequilibrium conditions as well as fabrication of structures and devices for ultrafast magnetic recoding and spintronics.

With the systematic studies we will find optimal materials, parameters and conditions for the fastest and the most efficient laser control of magnetism at the nanoscale. This will be accomplished by combining the unique expertise of the academic and industrial partners, which are world leaders in their own fields. The participation of industrial partners will further provide the necessary feedback on the integration of the foreseen novel technology with potential applications. The overall strategy of our work can be present as follows:

- using femtosecond circularly polarized laser pulses we will achieve subpicosecond magnetization reversal
- with systematic studies we will find optimal materials, parameters and conditions for the fastest and the most efficient laser control of magnetism at the nanoscale
- using an atomistic and multiscale computational approach we will simulate the process of ultrafast laser-induced magnetization reversal at the nanoscale and design structures for faster and denser opto-magnetic recording
- using state-of-the-art technology we will fabricate metallic and semiconductor nanostructures for ultrafast laser-induced magnetization reversal at the nanoscale
- using adaptive control of spectral amplitude, phase and polarization of laser pulses we will realize subwavelength localization of the opto-magnetic excitation
- we will demonstrate ultrafast magnetic recording at the nanoscale and ultrafast optical programming of nanospintronics devices
- using knowledge obtained during these studies conceptual designs of ultrafast magnetic recording and spintronic devices will be suggested.

The research program was organized in four closely connected workpackages in addition to one for management (see also Fig. 1.2):

WP.1. Ultrafast magnetization reversal
WP.2. Nanolocalization of opto-magnetism
WP.3. Fabrication and Characterization
WP.4. Conceptual designs
WP.5. Consortium Management, exploitation/dissemination of knowledge and results
WP.6. Scientific Management

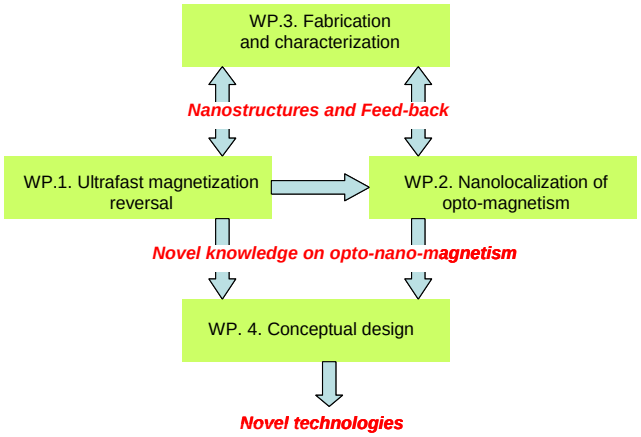

Fig. 1.2. Schematic representation of the workplan broken down into work packages and their mutual interdependencies.

1.3 A description of the main S&T results/foregrounds

The objectives of UltraMagnetron were translated in a number of deliverables distributed over 5 workpackages. In principle, all objectives were achieved and all deliverables were

delivered, although some were unavoidably less successful than others. Below we will first summarize the achieved objectives and then give a description of the main S&T results and deliverables.

Summary of achieved objectives:

- Novel mechanisms and approaches of magnetization reversal at sub-100 ps time-scale in continuous films and structures with size down to 200 nm have been discovered and theoretical understanding has been vastly improved
- Novel approaches for laser control of nanomagnetism at the picosecond time-scale which could not be even predicted before were discovered
- Knowledge accumulated in the project has been transferred to industries. Seagate and Philips have analyzed the future of the opto-magnetic technology in commercial devices suggesting a conceptual design for opto-magnetic read-head and required picosecond laser. NXP sees no product application for spintronic devices in their future development because of strategic changes in the company. All-optical switching has made it to the roadmap of the HDD industry, as the next technology after HAMR. The consequence would be that a production of 400 million lasers each quarter to be incorporated in write heads. According to an analysis of Philips, this is potentially doable.

WP 1. Ultrafast magnetization reversal

The workpackage aims

- to obtain novel fundamental knowledge on ultrafast opto-nano-magnetism and ultrafast magnetization dynamics at the nanoscale

- to define the conditions and parameters that provide the fastest and the most efficient laser control of magnetism in nanomagnets.

Task 1.1. Rare-earth transition metal alloys

A. Aimed deliverable: Report on the optimal composition of RE-TM-alloy (TM=Fe,Co; Re=Gd,Tb,Sm,Dy,Nd,Y) that provides the most efficient and fastest laser-induced magnetization reversal. It is expected that the report will reveal how efficiency and speed of the laser-induced magnetization reversal are affected by intrinsic magnetic properties.

B. Progress

Extensive studies of various compositions of Re-TM alloys have been performed for TM=Fe, Co and Re=Gd, Tb, Dy, Nd. Our measurements showed that only the samples with Gd concentration in the range of x=22-26 %, with Tb concentration of x=14-16% and with Dy concentration of x=14-20% possess magnetization and angular momentum compensation points within the studied temperature range. All-optical switching was observed in samples with Gd concentration in the range of x=22-28 %, with Tb concentration of x=16-20% and with Dy concentration of x=22-24%.

Further we performed time-resolved studies of the all-optical switching and this study led to rather unexpected results. It is generally accepted that the fastest way for reorienting spins is realized via precessional motion in an external magnetic field. Our experiments, supported by theoretical calculations, clearly show another new mechanism for

magnetization reversal which does not involve precession. Instead, under the action of the laser pulse the magnetization of a ferromagnetic thin film first collapses on a subpicosecond time scale, while long after the action of the laser, it reappears in the direction defined by the polarization of the pulse (see Fig.1.3.1). Passing through a state of quenched magnetization seems to be the key to obtain ultimate magnetic switching speed. Once the system is in a quenched state, the strong magnetic exchange interaction between electrons will rapidly restore ferromagnetism. Harnessing electron exchange—the strongest force in magnetism—is certainly a very promising way to achieve ultrafast switching.

The evolution of the magnetization after the excitation by a single laser pulse, observed in our experiment, is in good agreement with the scenario for linear reversal, proposed by the group of the University of York (P2). As in the simulations of P2, the reversal proceeds via a strongly-nonequilibrium state. Moreover, the reversal is observed only in a narrow range of intensities (~10 %), exactly as predicted by the simulations.

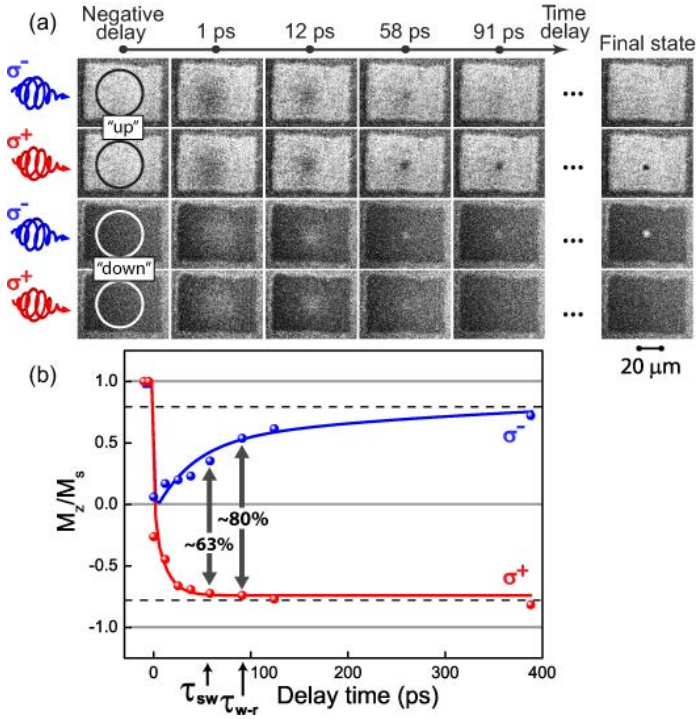

Fig. 1.3.1. (a) The magnetization evolution in Gd24 sample after the excitation with right- (σ^+) and left-handed (σ^-) circularly polarized pulses at room temperature. The domain is initially magnetized "up" (white domain) and "down" (black domain). The last column shows the final state of the domains after a few seconds. The circles show areas actually affected by pump pulses. (b) The averaged magnetization in the switched areas (~5μm) after the laser pulses of opposite helicities, as extracted from the images in (a) for the initial magnetization "up".

Again, to understand the dependence of the write-read time on the magnetic properties of the samples we performed time-resolved single-shot measurements at different temperatures. The obtained dependence of the write-read time on the difference between the sample temperature and the compensation temperature is shown in Fig. 1.3.2.

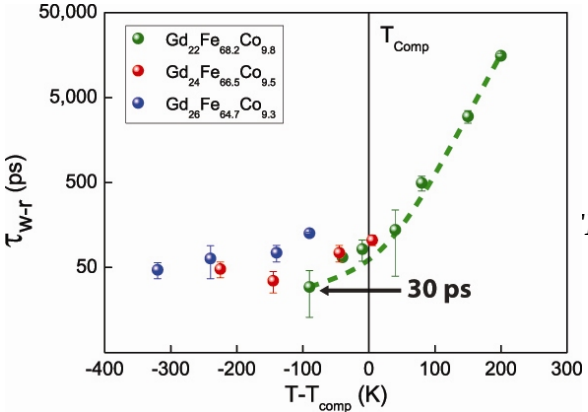

Fig. 1.3.2. Dependences of the write-read time $\tau_{w\text{-}r}$ on the relative temperature

T-T_{comp} for Gd22, Gd24, and Gd26 samples. We achieved magnetization reversal within 30 ps for Gd22 at T=10 K. The dash line is guide to the eye.

As can be seen from Fig. 1.3.2 the write-read time is the fastest and nearly temperature-independent below the compensation point for all samples. In sample Gd22 we achieved a write-read time of 30 ps, which is just 3 times longer than the one predicted from the simulations of partner P2 (York). Nevertheless, the data show that using this method we were able to record the magnetic information by a subpicosecond laser pulse and read it out by a similarly short pulse within 30 ps, which is the fastest write-read event demonstrated for magnetic recording so far. The simulations also show that the all-optical magnetization reversal in nanomagnets may operate even faster reaching subpicosecond time-scale.

C. Significant results/Foreground

- The fastest reversal times are achieved for sample temperatures in the vicinity and below the compensation temperature.
- The efficiency (in terms of required laser intensity) of the all-optical magnetization reversal increases upon approaching the compensation either from above or from below.
- By varying the temperature we achieved a write-read time of 30 ps, which is the fastest write-read event in magnetic recording demonstrated so far.
- Materials with compensation point are shown to be very promising media for magnetic recording.

D. Critical assessment of the progress

The deliverable has been achieved, though it took somewhat longer than anticipated.

Task 1.2. Diluted magnetic semiconductors

A. Aimed deliverable: Report on speed and efficiency of laser control of domains in magnetic semiconductors

B. Progress

We have undertaken a study of the dynamics of the photo-induced reduction of the coercive field observed in a (Ga,Mn)As film. Static experiments have already demonstrated that exposing the film to light substantially reduces the coercive field during the exposure (more that 60% at an illumination of approximately 1 W cm^{-2}). These further experiments demonstrate that the effect is both faster and more efficient than previously thought. In fact, by using a short (sub-picosecond pulse) the coercive field can be reduced almost to zero in an area of approximately 100 μm^2 using only 0.08 nJ of energy. This compares very

favourably with the efficiency of current hard drives which require about 8 nJ of energy per bit written.

A mode-locked Ti:Sapphire laser is used as a source of short pulses of light. It generates a train of pulses, each having duration of approximately 90 fs and an energy of about 6 nJ. The time between pulses is fixed at 12.5 ns. To separate individual pulses from the train a pulse picker is employed. This works as an electronic shutter, only allowing a pulse through when an electro-optical modulator is activated. Using the pulse picker, the time between pulses can be increased to 1 ms and above. Figure 1.3.3 shows magnetic hysteresis loops of the (Ga,Mn)As, measured by MOKE, with and without pulses at 100 Hz. In the presence of 0.08 nJ pulses the photo-coercive effect (PCE) results in a 97 % reduction in the coercive field.

Systematic experiments showed that the reduction of the coercive field was not a linear function of the pulse energy (see Fig 1.3.4). The nonlinear power dependence of the photo coercive effect (PCE) is consistent with that previously observed in the static measurements. It was also noted that the pulse repetition rate had no effect on the reduction in coercive field; in fact, slow repetition rates (0.2 Hz) demonstrated that a single pulse was sufficient to induce the full reduction observed.

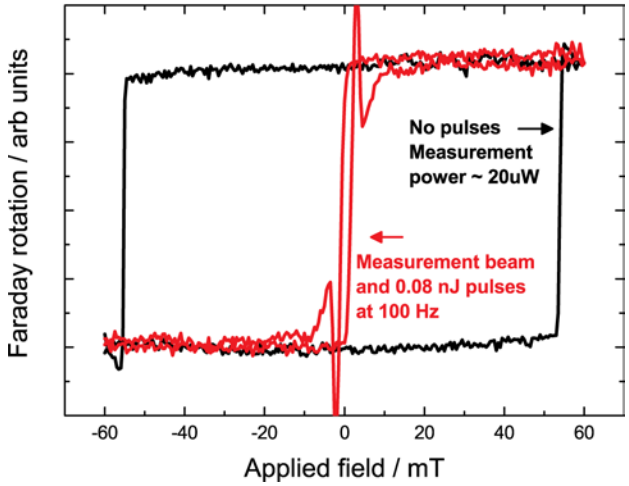

Figure 1.3.3. Static MOKE measurements of the magnetic hysteresis of (Ga,Mn)As at 1.6 K measured with an incident power of 20 μW. The black curve shows a measurement without incident pulse, while the red curve shows a measurement where the sample was exposed to 0.08 nJ pulses at 100 Hz (incident power 8 nW).

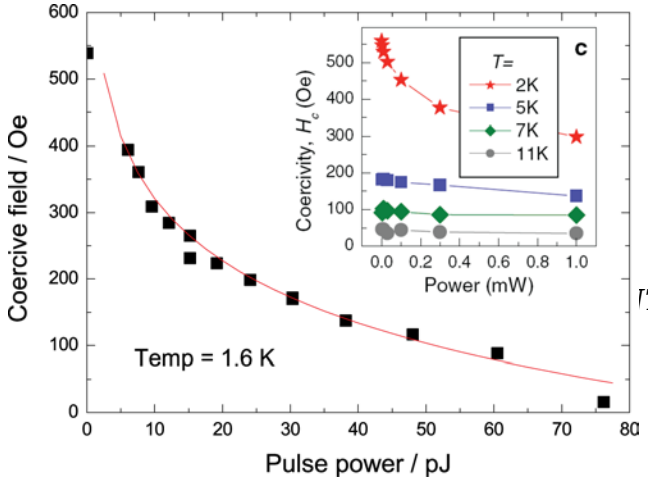

Figure 1.3.4. The coercive field of (Ga,Mn)As as a function of the incident pulse energy. The line shows a logarithmic fit to the experimental data. (The inset shows pervious static

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measurements of the coercive field for continuous excitation).

C. Significant results

- The photo-coercive effect in (Ga,Mn)As is demonstrated to be an extremely efficient way of writing magnetic information (a single 100 fs 0.08 nJ pulse is sufficient to cause 97% reduction in the coercive field). Unfortunately, laser control of magnetism in (Ga,Mn)As appears to operate at a nanosecond time-scale (see tasks 1.3 and task 2.1) which is by far slower than the range aimed in this project.

D. Critical assessment of the progress

The deliverable has been achieved.

Task 1.3. Ultrafast magnetization reversal with shaped pulses

A. Aimed deliverable: Report on the optimal parameters of the laser pulse (power, wavelength, duration, spectra, chirp, temporal profile) that provides the most effective laser control of magnetism in RE-TM-alloys and DMS.

B. Progress

RE-TM-alloys

In order to investigate the influence of the laser pulse properties on the switching we performed measurements changing the pulse duration by chirping (80fs-2500 fs) and by using a ps laser source (pulse duration 11ps), the central wavelength (400nm-800 nm), the spectral bandwidth (comparing the results obtained for fs and ps lasers), as well as the repetition rate (single pulse- 500 kHz). Further we varied the angle of incidence up to 30 degrees and the polarization. Additionally we used a pulse shaper to modulate the amplitude and the spectra of the pulse. Finally we also investigated the influence of heating in more detail by implementing a pump-pump-experiment. The experiments were performed for two different samples Gd24 and Gd26. Summarizing we obtained the following results (qualitatively the same for both samples):

- all-optical switching works even for ps-laser pulses
- the threshold fluence hardly changes with increasing pulse duration
- all-optical switching works for all investigated wavelengths within the visible range
- no systematical changes were observed when limiting the pulse spectra, in particular all-optical switching works for very narrow bandwidths
- for increasing repetition rate the minimal threshold fluence decreases
- all-optical switching works for the investigated incident angles up to 30°

- no systematical changes were observed when using sinusoidal shaped pulses
- a clear influence of heating on the effect of all-optical switching was determined in the pump-pump-experiments

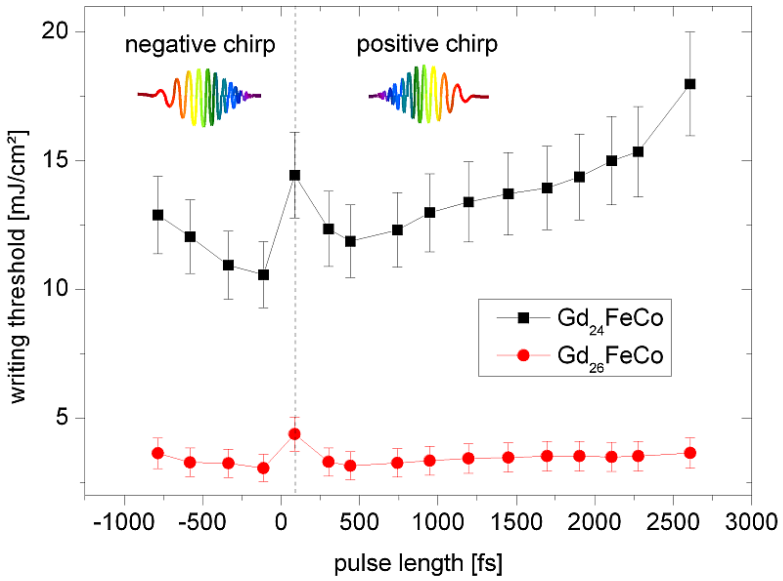


Figure 1.3.5. Dependence of switching laser fluence on pulse duration for both Gd24 and Gd26. The picture is divided into regions of positive and negative chirp respectively by the dashed line and negative chirps are denoted by a negative sign of the pulse duration value. For both samples only a small variation in threshold power can be found for a large range of pulse durations

DMS

It is evident from a comparison of the PCE for continuous and pulsed excitation that the efficiency is greatly enhanced if energy is delivered to the system quickly (see task 1.2). This is evident in Fig. 1.3.3 where the addition of pulses leads only to a negligible increase in the incident power (+0.04%), but has a dramatic effect on the coercive field. This indicates that the PCE has a well defined lifetime in the material. By a comparison of the power required in the static measurements to the energy required for a similar reduction in the pulsed experiment it is clear that the PCE must decay on a timescale of a few nanoseconds.

To directly measure this timescale a double pulse experiment was performed. Here the reduction in the coercive field is measured as a function of the delay between two pulses. A schematic of the experiment is shown in the inset of Fig. 3.9. The incident light pulse is first divided in two, one half of the pulse travels a fixed distance to the sample while the other half travels a path which can be lengthened using a mechanical delay line. Both

pulses then reach the sample at a known delay with respect to each other. At zero delay between the pulses, the PCE corresponds to that induced by the sum of both pulse energies; however, as the delay is increased the reduction in coercive field tends to that observed with the individual pulse energies. The magnitude of the PCE thus decays as a function of the delay between pulses, see Fig. 1.3.6. An exponential fit to the data shows that the PCE relaxes with a time constant of approximately 1.5 ns.

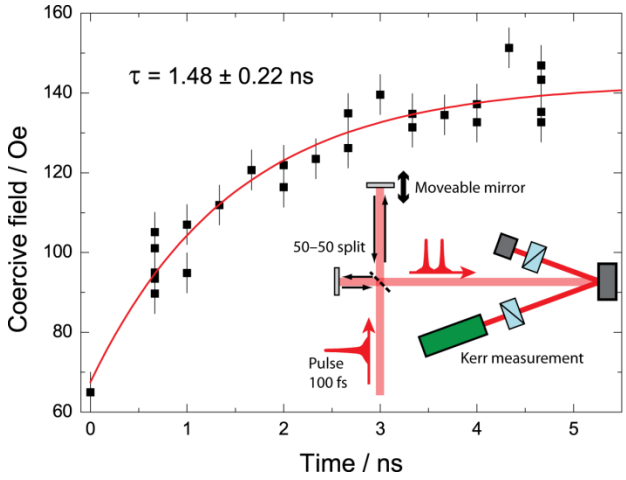


Figure 1.3.6. Coercive field as a function of the delay between two pulses. A schematic of the measurement apparatus is show in the inset. Measurements show that the photo-induced reduction in coercive field tends towards the single pulse level as the delay between the pulses is increased. Fitting the data shows a characteristic time constant of 1.5 ns.

C. Significant results

- 2 ps and even longer laser pulses cause magnetization reversal in GdFeCo alloys. This is a very promissing result for possible application of all-optical magnetization reversal in electronic devices, since generation of picoseconds pulses by miniaturized semiconductor lasers seems to be a solved problem.
- Photo-coercive effect in GaMnAs is shown to be most effective for laser pulses much shorter than 1.5 ns, the time constant of the photo-induced coercive field.

D. Critical assessment of the progress

All research goals of this task have been achieved. The experiments on GaMnAs show that if the laser pulse is shorter than 1.5 ns, its shape does not play a role. Pulse shaping experiments on GaMnAs seems to be unnecessary and thus have not been done.

Task 1.4. Atomistic modelling of the ultrafast laser-induced magnetization reversal

A. Aimed deliverable: Report on model for atomistic simulations

B. Progress:

The York and Konstanz groups have carried out the development of models for the physical understanding of the opto-magnetic process and the long-term device modelling. The models (described in the following sections) have given an understanding of the thermal processes involved in the opto-magnetic reversal process.

Our model calculations agree well with experiments at Nijmegen (participant P1) and demonstrate that the opto-magnetic reversal occurs via a strongly non-equilibrium magnetisation state in a mechanism we term ‘linear reversal’. The speed of the opto-magnetic reversal is explained in terms of the very fast (longitudinal) relaxation processes involved in the reversal.

Our atomistic model is based on the use of the Heisenberg formalism for the exchange interaction between atomic spins. With this we demonstrated that ultrafast reversal can occur on heating close to the Curie temperature in the presence of a large applied field. The reversal occurs via a novel ‘linear’ mechanism in which the magnetisation falls rapidly to zero followed by a recovery of the magnetisation into the field direction. The whole process occurs within tens of picoseconds; within the timescale of the experimental observations. However, the process is critically dependent on reaching the Curie temperature without going too far beyond, since this leads to loss of the reversed magnetisation. Having established the basic physics of the reversal we carried out further detailed calculations using a model based on the Landau-Lifshitz-Bloch (LLB) equation.

The LLB equation has the property that the magnetisation is not conserved which means that it can be used in calculations at elevated temperatures up to and even beyond the Curie temperature. This is an important step and the LLB equation will form the basis of our device simulations. In a single spin approximation, the LLB equation is computationally efficient and the influence of a magnetic field on the recovery phase following a rapid heat-pulse was investigated. This field originates in the laser-pulse due to the inverse Faraday effect.

It was found that the maximal electron temperature as well as the field pulse duration influence the reversal of the magnetic system: if the electron temperature is not high enough to fully demagnetize the magnetic system, no helicity-dependent reversal occurs. If the electron temperature is high enough to fully demagnetize the system the magnetization reverses towards the opposite direction due to the magnetic field. If the electron temperature is too high, although the system is fully demagnetized, no reversal occurs. These three regimes were also observed experimentally in the Nijmegen group (P1). Furthermore, it has been shown numerically as well as experimentally that the occurring reversal is not precessional in nature, but has instead a linear character, proceeding via a strongly-nonequilibrium state. The so-called linear reversal model leads to reversal processes on an ultrashort time scale consistent with the results of partner P1 (see task 1.1)

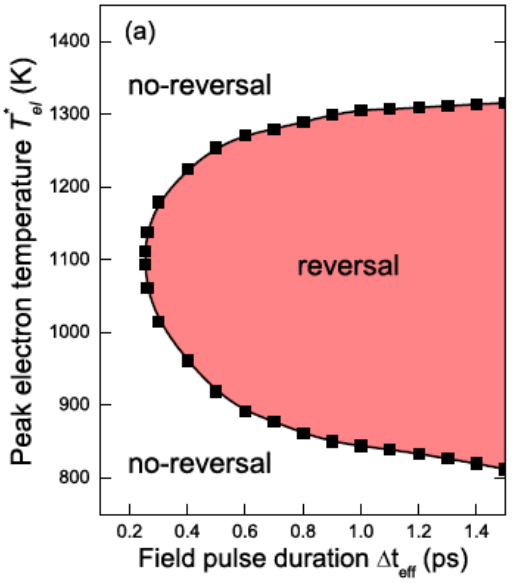


Fig 1.3.7. Phase diagram for the opto-magnetic reversal showing the combinations of peak electron temperature and duration of the effective magnetic field for which all-optical magnetization reversal occurs.

Our main result is shown in fig 1.3.7, which shows a phase diagram for opto-magnetic reversal. For a given pulse field duration the application of too low a temperature results in no reversal, while too high a temperature destroys the magnetisation after reversal. This shows that it is critical to achieve the correct laser power at short pulse durations. In our calculations the reversal 'window' opens up for a pulsed field time of 250fs. According to the calculations the reversal triggered by longer pulses is also possible, in agreement with the results of task 1.3 by P5.

We have also continued the atomistic modelling with the development of a model of a ferrimagnetic material such as GdFeCo. The reason for this is that ferrimagnets are complex materials having a magnetic compensation point which may contribute to the ultrafast reversal. It is important to study the dynamics of ferrimagnetic materials in order to understand their ultrafast dynamic magnetisation properties.

C. Significant results

- A phase diagram for opto-magnetic reversal was obtained, demonstrating a window of peak electron temperature and effective magnetic field pulse duration for opto-magnetic switching
- A new mechanism of linear magnetization reversal was discovered

D. Critical assessment of the progress

The goals have been fully achieved.

Workpackage 2. Nanolocalization of opto-magnetism

Objectives

- **to obtain a basic understanding of ultrafast laser-induced magnetization reversal in nanomagnets**
- **to develop adaptive controlled polarization pulse shaping for subwavelength localization of opto-magnetic effects**
- **to demonstrate highly efficient optical control of magnetism at the nanoscale**

Task 2.1. Ultrafast magnetization reversal in nanomagnet arrays

A. Aimed deliverable: Report on the efficiency of the laser-induced magnetization reversal as functions of the size of the nanomagnets (ranging from 2 μm down to 100 nm).

A. Progress

Working on this task we have discovered a novel mechanism of magnetization reversal in magnetic micron and submicron structures. It is generally accepted that magnetization reversal should be driven by a stimulus represented by a polar or axial vector such as magnetic field, electric current, electric field or cross-product of two electric fields. Here we discovered numerically and demonstrated experimentally a novel mechanism of magnetization reversal in ferrimagnet excited by an ultrafast heat pulse alone. The mechanism does not require the presence of any other stimulus and occurs each time when a heat pulse excites magnetic sublattices of a ferrimagnet on a time-scale of the exchange interaction between them.

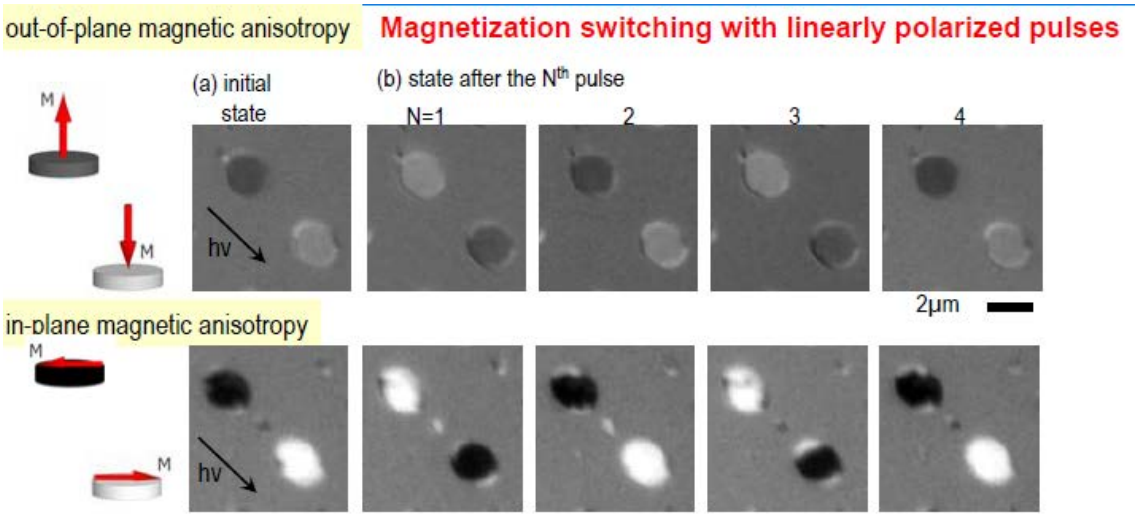


Fig. 1.3.8. XMCD images at Fe L_3 edge of $Gd_{25}Fe_{65.6}Co_{9.4}$ microstructures with magnetization lying in out-of-plane and in-plane direction. The XMCD contrast is obtained

after the initial state (a) and after every following laser pulse (b). The black arrows indicate the direction of the incoming x-rays.

Applying linearly polarized femtosecond laser pulses on a broad range of samples and structures we studied the newly discovered effect of magnetization switching by a heat-pulse-only in more detailed. We found that, for structures sizes down to 500 nm, a smaller fluence is needed with decreasing structure size. This small fluence dependence of a few percent might be related with a thickness variation of the structures due sputtering of the film through the lift-off mask, but currently we don't have a full explanation for the fluence dependence. We also observed heat-pulse-only switching for smaller structures, down to 100 nm, however, the quantitative interpretation is difficult due to the mixture of in-plane and out-of-plane domains in the smaller structures.

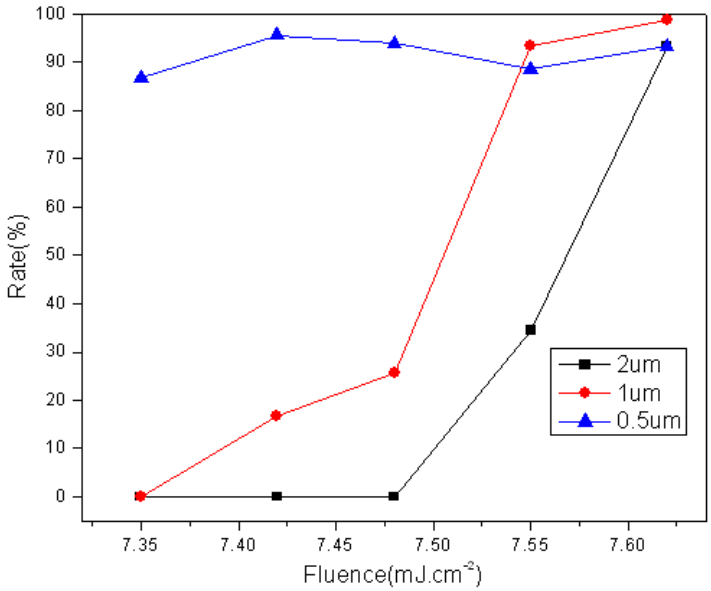


Fig. 1.3.9. Switching rate for 2, 1, and 0.5 micrometer size structures as function of the fluence. Note that the fluence is more a relative measure since we don't have a precise enough measurement of the laser spot size on the sample.

Nevertheless, performing experiments with 400 nm structures we found that within the structure a 200 nm small out-of-plane domain is formed which we can repeatable switch with single linearly polarized laser pulses. For this, it was essential to determine the 3 dimensional magnetization map. From the 3 XMCD images of the same region recorded with 3 different incoming X-ray azimuth angles of 0, 270 and 180 degrees, the three dimensional Fe sublattice magnetization vector M is determined (see Fig. 1.3.10.). For the initial state of the sample, i.e. before the excitation with a single laser pulse, its in-plane projection M and its out-of plane projection are shown in the middle of Figure 1.3.10. In these images, the hue gives the direction while the brightness gives the size of the magnetization according to the in and out-of-plane color wheel on the left in Figure 1.3.10. respectively. While the continuous film displayed no in-plane contrast (not shown), all the structures larger than 200 nm diameter display clear in-plane magnetized domains at their

rim. For the smaller ones, the spatial resolution of the microscope prevents their measurements due to crosstalk between domains with magnetization in different directions.

The 3-dimensional magnetization of the same structures after a single laser pulse is shown in the lower line of Figures 1.3.10. From these measurements, one can conclude that the switching behavior of the edge and inner part of the structure are largely uncorrelated. The smallest domain size for which we achieved the laser induced magnetization reversal is the 200 nm wide out-of-plane domain at the center of the 400 nm wide square. The in-plane domains at the outer rim are most likely due to a change of the anisotropy of the amorphous GdFeCo as a result of a small oxidations and a thickness variation at the outer rim.

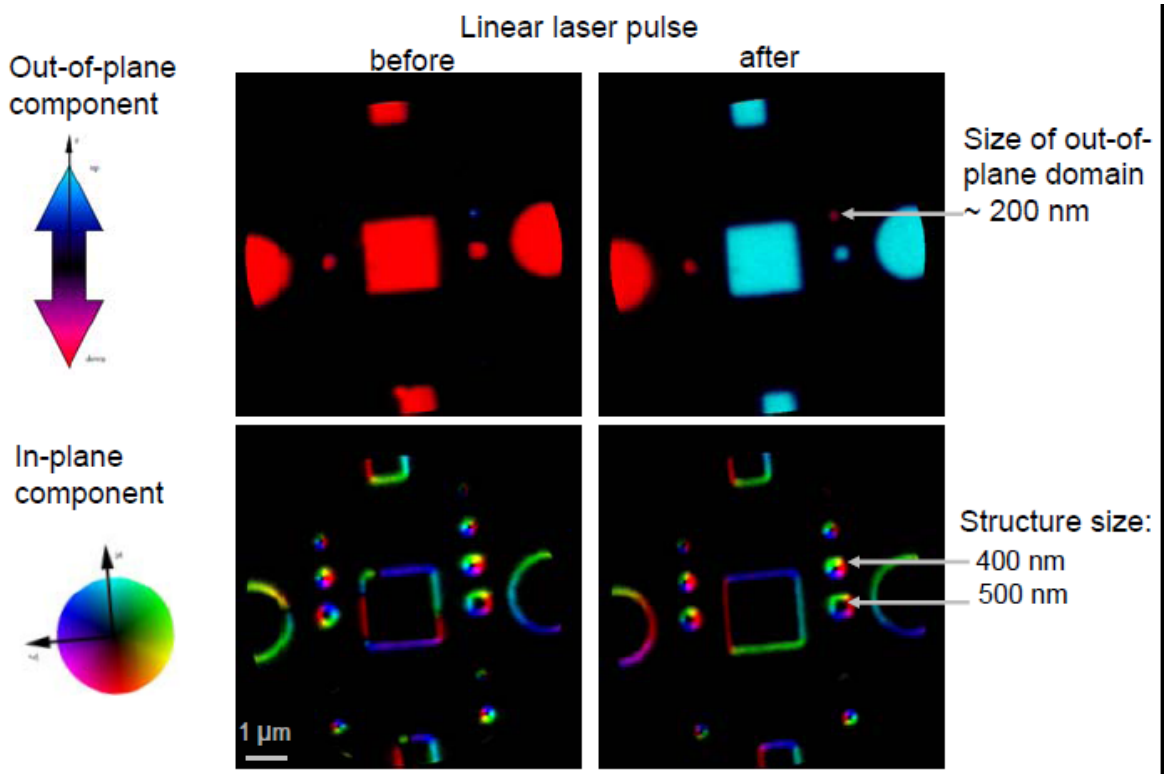


Fig. 1.3.10. Laser-induced switching of 200 nm domain

We have also studied ultrafast magnetization dynamics in an array of 200 nm GaMnAs structures. We have succeeded to achieve the conditions required for laser-induced destruction of the net magnetization. Nevertheless, the dynamics of the demagnetization

appeared to be very slow, in the range of 100 ps, demonstration that these compounds are not suitable for the purposes of ultrafast magnetic recording aimed in this project.

C. Significant results

- Novel mechanism of magnetization reversal with an ultrafast heat pulse only has been discovered. It shows that all-optical magnetic switching can be also realized with linearly polarized or even unpolarized laser pulses

- Fluence dependence of the switching rate in the samples of various sizes have been investigated and revealed that smaller structures require smaller laser fluence for the switching

- Magnetization dynamics in GaMnAs nanostructures appears to be slow (~100 ps).

D. Critical assessment

Although structures with sizes down to 100 nm have been investigated, the results obtain for structures smaller than 500 nm are not really conclusive. However, within 400 nm structure we have succeeded to switch a domain which was as small as 200 nm. Studies on GaMnAs showed that this material is unsuitable for ultrafast magnetic recording.

Task 2.2. Development of adaptive control of polarization shaped laser pulses for subwavelength localization of opto-magnetic effects

Aimed deliverable: Report on the feasibility of sub-wavelength localization of opto-magnetic effects

A. Progress

Initial strategy based on plasmonic antennas

After several months of dedicated research we finally succeeded in preparing gold cross antennas on top of the GdFeCo film (see Fig. 1.3.11). It turned out that at least with respect to technical limitations no additional spacer layer is needed in order to get PEEM-images and to avoid a charging of the sample. Moreover, if one considers the limited penetration depth of the near fields produced by the nano-antennas this is the optimal condition due to the fact that the nano-antennas are as close as possible to the GdFeCo substrate.

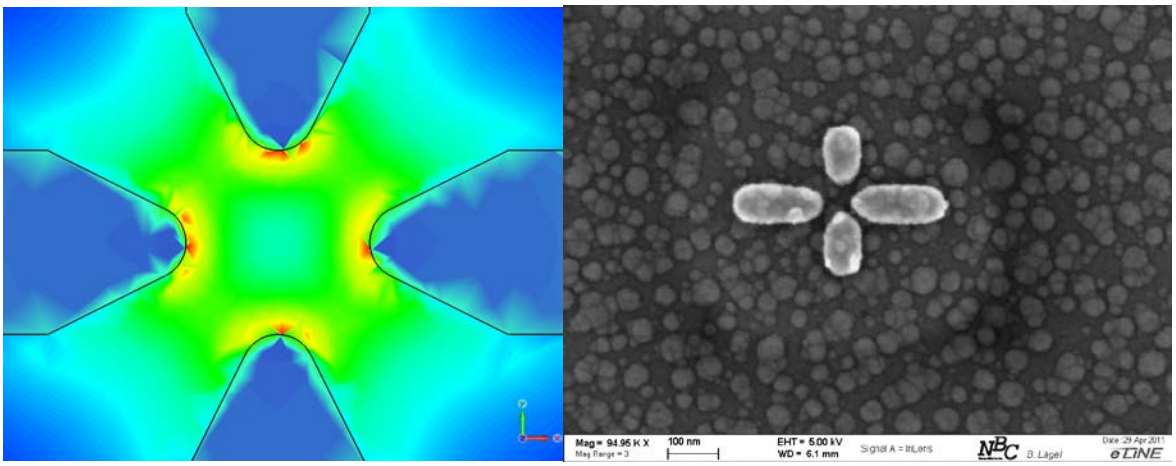


Fig. 1.3.11. left: Simulation to prove the circular polarization of the nearfields in cross antenna structures, right: Gold cross antenna on top of the GdFeCo sample

approach was not successful as the ITOP layer thicknes must be in the order of some 10nm to guarantee a closed film. Unfortunately such a layer thickness does not allow the nearfields to penetrate into the magnetic substrate.

Further we illuminated the nanostructures with 11 ps laser pulses (central wavelength= 532 nm) with a laser fluence estimated to correspond to the fluence needed to switch all-optically. We observed that most of the gold antennas were destroyed.
In addition, we also observed a degradation of the nano-structures without any laser illumination. Facing such problems we decided to follow alternative research approaches to the problem of nanolocalization of opto-magnetic effects. One them is developing an alternative design of the antennas, another – advanced use of far-field technqiues.

Advanced design of nanoantennas
In order to avoid the above mentioned problems that do not allow obtaining a high-quality long-living plasmonic antennas we suggested another design of the latter. As sketched in Fig. 1.3.12 we used a combined process of focused ion beam (FIB) milling and a lithography process to produce the nanostructures within the substrate material. Fig. 1.3.13 (a) and (b) show the result of the FIB processing before the structures are evaporated with gold. The structures are milled in the substrate with very high precision. Fig. 1.3.13 (c) and (d) show the system for the two different approaches sketched in Fig. 1.3.12 after the lift-off. In both cases the lift-off was not complete and the structures could not be separated.

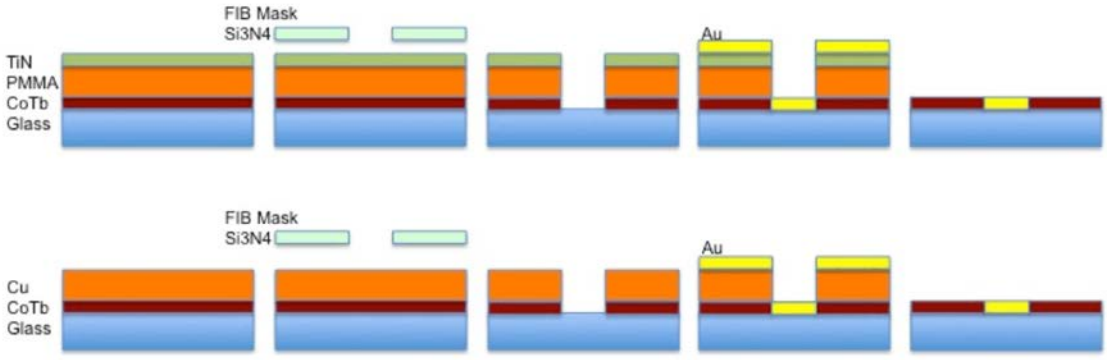


Fig.1.3.12 Two different kinds of sample preparation producing nanoantennas within the magnetic material

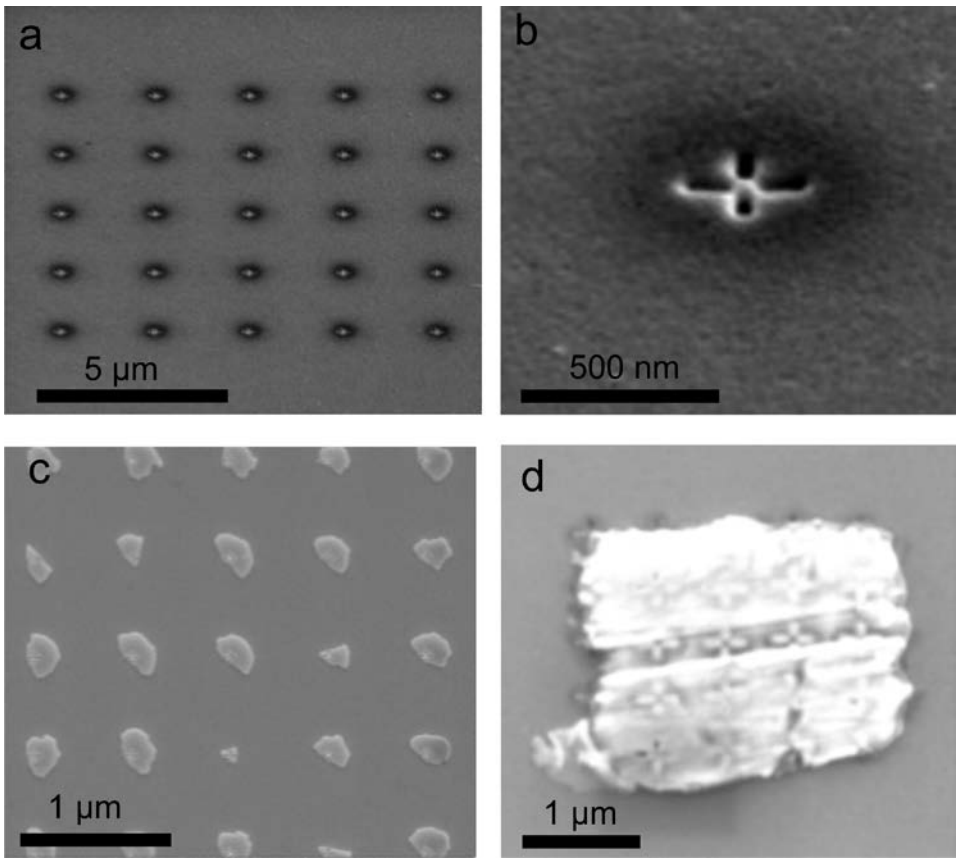


*Fig.1.3.13. SEM images of the new nanostructure system. **a** and **b** show the inverse nanostructure in the substrate material, produced by FIB just before the gold*

Advanced far-field techniques (CONFIDENTIAL. The result is under embargo).

CONFIDENTIAL

As it has been demonstrated above, all-optical magnetic switching occurs in a narrow range of intensities. Moreover, if the laser spot is larger than the minimum size of the magnetic domains, one may reach conditions when light records magnetic domains smaller than the laser spot. The minimum size of a stable magnetic domain in TbFeCo is much smaller than in GdFeCo and canbe down to 100 nm. We have employed this fact for sub-wavelength localization of opto-magnetic effects. Using 100 fs laser pulses with central wavelength 800 nm and focusing them with the help of a confocal microscope on a TbFeCo thin film we have succeeded to achieve conditions under which subwavelength magnetic domains are created in a reproducible way. For the detection of the domains, a Scanning Near Field Optical Microscope (SNOM) was employed.

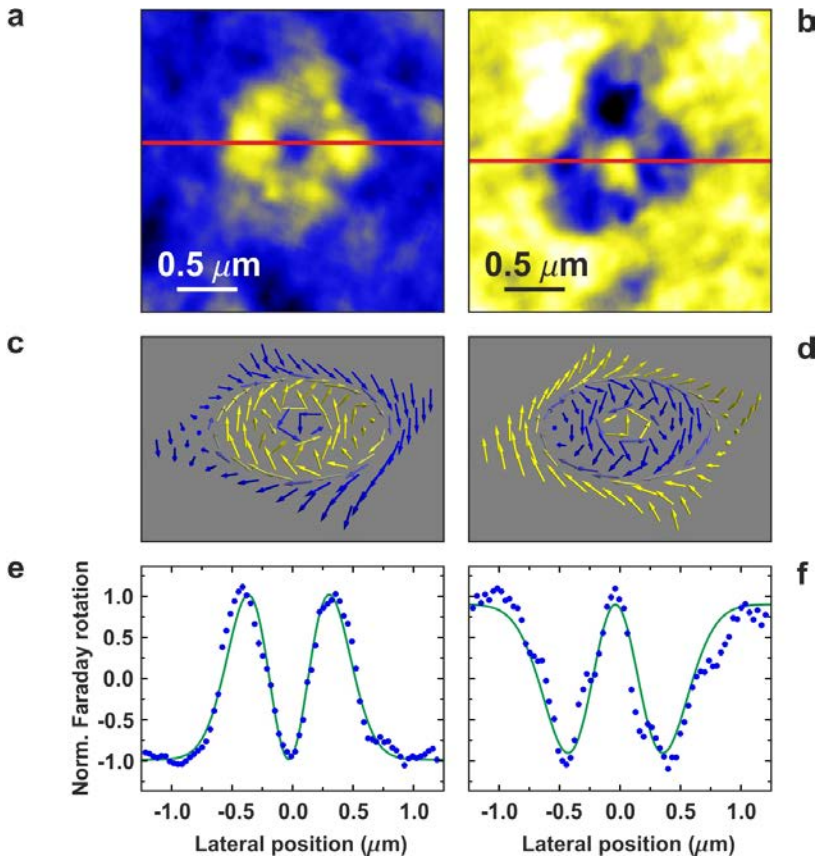


Fig. 1.3.14. **CONFIDENTIAL. THE PICTURE IS STILL UNDER EMBARGO.** (a, b) Optical near-field Faraday rotation maps showing "doughnut"-shaped subwavelength magnetic domains induced in a thin TbFeCo film after single laser pulse irradiation (energy density: ~7 mJ/cm^2) in film areas showing opposite out-of plane magnetizations. (c, d) Spin textures correspondent with the induced structures.

C. Critical assessment of the progress

- The goal showing the possibilities and limits of nanolocalization of opto-magnetic effects by using plasmonic antennas has been achieved. Despite all the efforts and

various approaches, nanolocalization of opto-magnetic effects with the help of plasmonic antennas is still challenging

- Subwavelength localization of opto-magnetic effects has been demonstrated employing advanced use of confocal optical microscope and TbFeCo-materials allowing stable magnetic domains down to 100 nm

Task 2.3. Laser induced magnetization reversal at the nanoscale

A. Aimed deliverables.

- Report on the feasibility of switching the magnetization within 1 ps.
- Demonstration of the laser-induced magnetization reversal faster than 100 ps and with spatial resolution below 300 nm.

B. Progress

Aiming to progress towards understanding the fundamental limits of speed of magnetic switching in nanostructures one had to start measurements in X-ray spectral range which intrinsically allows better spatial resolution in comparison with optical techniques. As a starting point we have decided to perform time-resolved magneto-optical studies of magnetization reversal in GdFeCo using X-ray techniques. Already at this stage of the studies we came across extremely unexpected results which could not be predicted from conventional theories of magnetism.

The measurements provided unexpected insights into the physics of magnetism, showing that ultrafast spin reversal in a material with antiferromagnetic coupling of spins occurs via a ferromagnetic-like state. In particular, optical excitation of ferrimagnetic GdFeCo on a time-scale pertinent to the characteristic time of exchange interaction between the rare earth (RE) and transition metal (TM) spins pushes the spin dynamics into a yet unexplored regime, where the two exchange coupled magnetic sublattices demonstrate substantially different dynamics. As a result, the reversal of spins appears to proceed via a novel transient state characterized by a parallel alignment of the net Gd and Fe magnetic moments, despite their ground-state antiferromagnetic coupling. The net magnetic moment of the RE(Gd) sublattice is found to reverse within 1.5 ps, which is substantially slower than the TM(Fe) reversal time of 300 fs. These surprising observations, supported by atomistic simulations, present a novel concept of manipulating magnetic order on a timescale of the exchange interaction. Magnetization reversal faster than 1 ps seems to be feasible but one has to be aware of the fact that on this time-scale different magnetic sublattices of a magnet may reverse their magnetization with different speeds.

Performing magneto-optical studies of ultrafast magnetic switching in GdFeCo-alloy in the visible spectral range one should be aware of the fact that such a detection technique will be mainly sensitive to Fe-sublattices. In this project we performed time-resolved magneto-optical studies in the visible spectral range and studied ultrafast dynamics of the Fe-magnetization in GdFeCo-microstructure with sizes down to 500 nm. However, studies for structures below 1 μm provided inconclusive results. It is seen that the Fe-sublattice can reverse its magnetization faster than 1 ps. The measurements reveal that smaller structures require less intensity to achieve the all-optical switching.

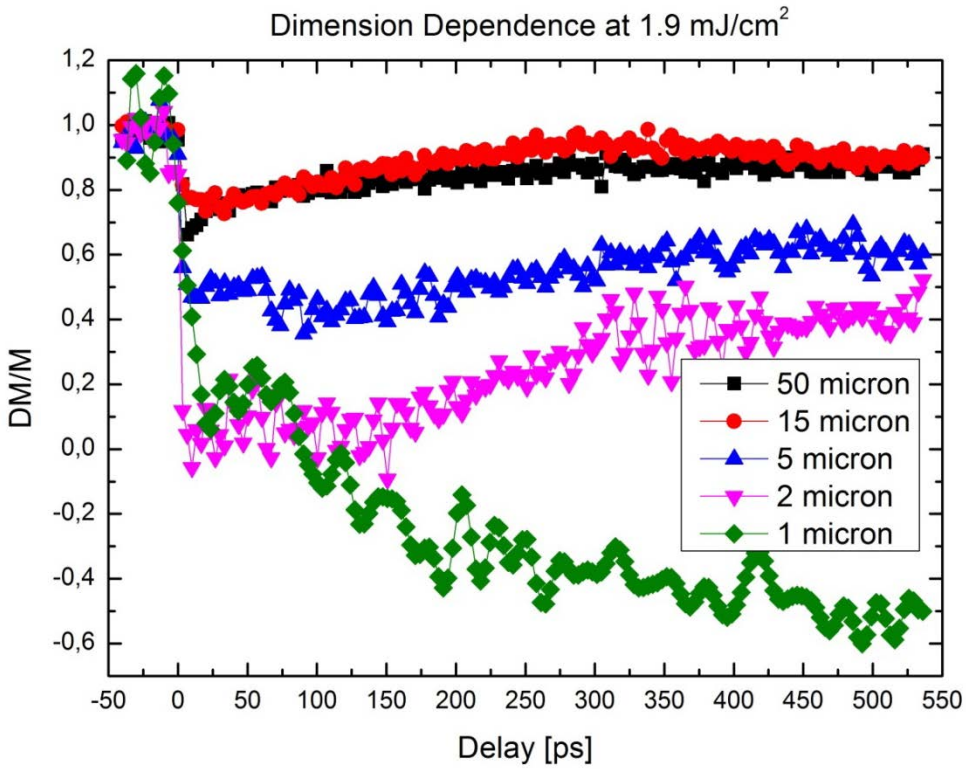


Fig.1.3.15. Magnetization dynamics as a function of sample sizes and fixed laser fluence of 1.9 mJ/cm^2

We have also performed measurements using an X-ray photoemission electron microscope and imaged the laser induced magnetization reversal in the microstructures with a spatial resolution better than 300nm and temporal resolution of 50 ps. For the excitation, 50 fs short linearly polarized laser pulses were focused on the sample with 16° grazing incidence. The magnetization direction of the sample is revealed in PEEM microscopy using the XMCD effect. A permanent magnet of 0.4T was inserted below the sample, thus allowing the resetting of the sample in its initial magnetic state before the occurrence of a new pump-probe event and also securing that the structures have an out-of-plane magnetization direction. . In Figure 1.3.16. XMCD images as function of time are shown. Comparing images obtained before and at 75 ps after the laser pulse event, it can be seen that the contrast has changed from white to black within a region of the structures. This change of the XMCD contrast is the proof that the magnetization direction reverses into the opposite direction after the laser pulse. In addition to the reversal against the applied magnetic field, we studied also the recovery into the initial state. The reversal into the direction of the applied magnetic is much slower (few ns) and occurs after nucleation via the movement of domain walls. Thereby an interesting domain pattern is developed, which forms particular geometric patterns that are dependent on the size of the structure (see Figure 1.3.16).

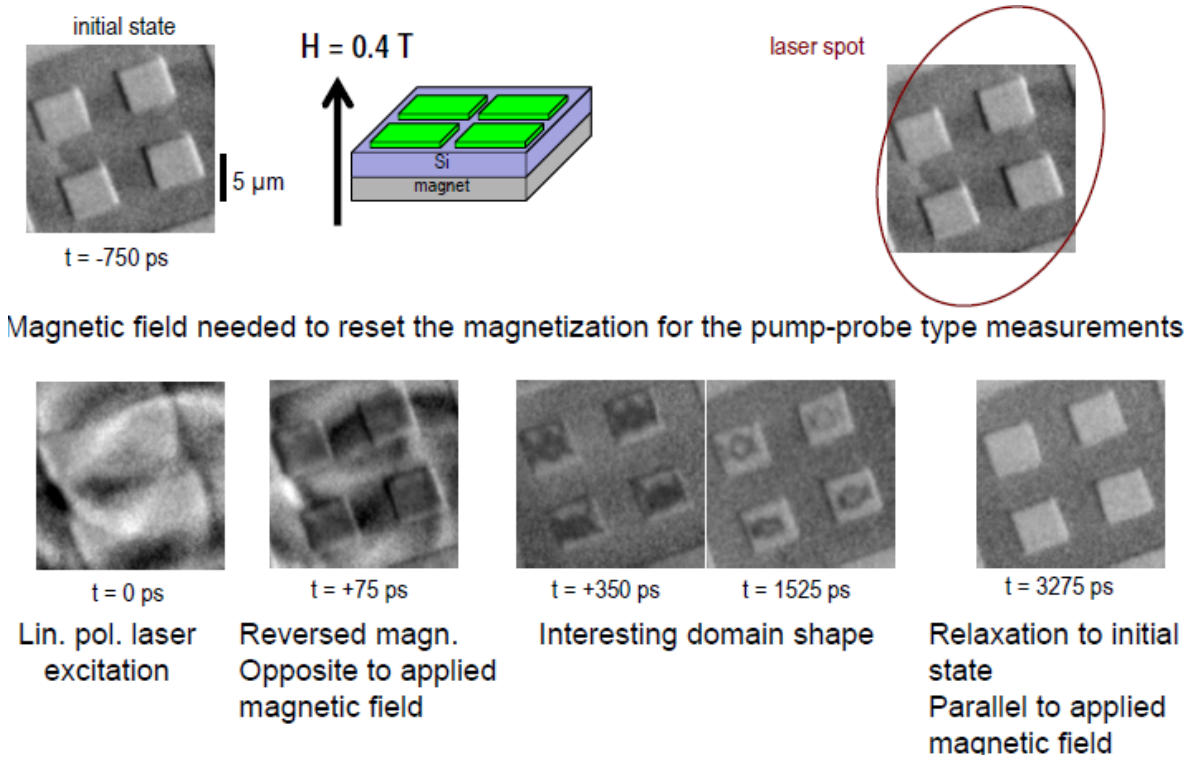


Fig.1.3.16. Laser-induced magnetization reversal faster than 100 ps and with spatial resolution below 300 nm as observed by PEEM.

C. *Significant results*

- Element-specific magnetization switching has been demonstrated showing that magnetization reversal on a time-scale of 1 ps or faster proceeds via a yet unexplored strongly non-equilibrium state, in which antiferromagneically coupled sublattices acquire ferromagnetic-like alignment.
- Subpicosecond magnetization reversal is possible but may occur only for one of the sublattices of a multisublattice magnet.
- laser-induced magnetization reversal faster than 100 ps and with spatial resolution below 300 nm is demonstrated

D. *Critical assessment of the progress*

The task has fully reached its goals, led to the discovery of unexpected results and opened new insight, into the problem of laser-induced magnetization dynamics at the nanoscale.

Task 2.4. Modeling laser-induced magnetization reversal at the nanodevice level

A. Aimed deliverable: Report on the computational program for modeling at the nanodevice level

B. Progress

As a first step, the groups in Konstanz and York investigated opto-magnetic switching processes of a single macro-spin in the framework of the Landau-Lifshitz-Bloch (LLB) equation recently derived by D. Garanin [Phys. Rev. B 55, 3050 (1997)]. It was found that the maximal electron temperature as well as the field pulse duration influence the reversal of the magnetic system. These findings coincide with observations found experimentally by P1 [see task 1]. Furthermore, it has been shown numerically as well as experimentally that the occurring reversal is not precessional in nature, but has instead a linear character, proceeding via a strongly-nonequilibrium state. The so-called linear reversal mode previously investigated analytically for a single LLB macro-spin leads to reversal processes on an ultra-short time scale. In the next step, we went beyond this single-macro spin approach and extended our approach to a LLB based multi-macro spin simulation. Therefore, the exchange coupling as well as the dipolar interaction were taken into account. Here, the long-range dipole-dipole interaction is calculated with the aid of the well-established fast-Fourier transformation (FFT). Furthermore, we parallelized our code in order to simulate extended systems of realistic size up to 10^7 macro-spins on our computer cluster at Konstanz.

With these new programs, we simulated systems with up to $4*10^6$ macro-spins. We assume a Gaussian electron temperature profile in order to model a realistic laser spot as used in the experiments. Fig. 1.3.17 shows the magnetization evolution after excitation with a circularly polarized laser pulse of a film with an area of 10 μm x 10 μm and a film thickness of 5 nm. The magnetization evolution corresponds to those found in the experiment

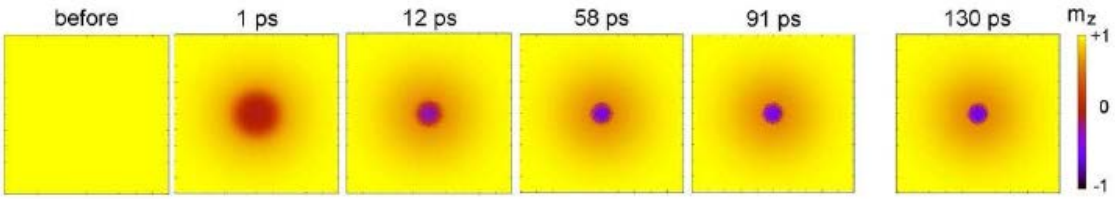


*Fig. 1.3.17. Magnetization evolution in a 10 μm*10 μm*5 nm film at 1 ps, 12 ps, 58 ps, 91 ps, and 130 ps is shown. The film is initially magnetized "up" (light color) before the laser spot is switched on. It can be seen that in the area affected by the laser pulse a small reversed domain (dark color) is formed within some picoseconds.*

C. Significant results

- A parallelized code to simulate magnetic arrays or single dots with system sizes between some hundred nanometers and some micrometresin a strongly non-equilibrium state, based on the LLB equation, has been completed and tested

- The magnetization reversal by a single circularly polarized laser pulse has been successfully simulated

D. Critical assessment of the progress
The task has fully reached its goals and resulted in development of new computational tools.

3. 3. WP 3. Fabrication and Characterization

Objectives:

- **to supply well characterized magnetic nanostructures for ultrafast laser control of magnetism at the nanoscale**

Task 3.1. Fabrication of metallic magnetic nanostructures
A. Aimed deliverables: Magnetic nanostructures based on RE-TM alloys and report on nanofabrication and magnetic, optical as well as magneto-optical characterization of the materials

B. Progress
We were exploring different structuring techniques of films with the composition $Gd_{24}Fe_{66.5}Co_{9.5}$ with Curie-temperature of 290°C and Compensation-temperature of 60°C. The film consisted of the following stacking: AlTi(10nm)/SiN(5nm)/GdFeCo(20nm)/ SiN(3nm). The difficulty is to design the sample such that the structures remain to have out-of-plane magnetic anisotropy and don't lead to the effect of charging in the PEEM experiment. Since the focus is to find first a structuring method we produced first only squares with 1*1 micrometer. After identification of the most promising structuring method, i.e. via lift-off a variety of samples with different sizes and designs were fabricated.

Focused Ion Beam (FIB):
FIB resulted in destroying the magnetism or turning the magnetization into the plane. Either FIB is destroying the magnetic structure in the proximity of the FIBed area or the capping layer which is removed by FIB is essential for the out-of-plane magnetization. If the lines created by FIB are too deep (through the whole film) the sample is charging in the PEEM and cannot be measured.

Pre-pattern
In this method first the substrate is patterned, next a layer of 2nm Ti and 8nm Pt is grown in order to increase the conductivity and then the GdCoFe film is grown on top. We were

exploring Si and Glass (Borofloat 33 from Schott) as substrate and were trying different heights of the structures.
On the glass substrate the magnetization stays out-of-plane on the structures while it turns into the plane off the structures. Since the surface of the structures is smooth while the surface off the structures is rough due to the structuring, we attribute this to strain effects onto the film. For the Si substrates the magnetization stays always out-of-plane and for 120 nm high structures we find that the structures and the area between the structures are decoupled.

Lift-off
First, a layer of 2nm Ti and 8nm Pt is grown on a glass substrate. Next, a PMMA mask with the negative image of the structures is created on the substrate and the GdFeCo film is grown on top. After removing (lift-off) of the PMMA only the structures are left. Squares and circles of 5000nm down to 100nm size have been produced (see Figure 1.3.18).

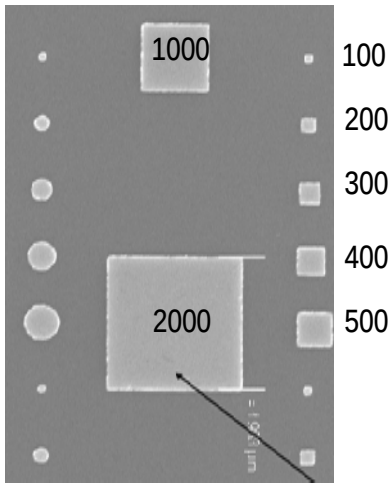


Figure 1.3.18. SEM image of an area of structures produced by lift-off.

C. Significant result

- We have successful structured GdFeCo film by lift-off and imaged the domain structure with PEEM.

D. Critical assessment of the progress
The task has fully reached its goals.

Task 3.2. Fabrication of semiconductors magnetic nanostructures
A. Aimed deliverables: Report on nanofabrication and magnetic, optical as well as magneto-optical characterization of DMS-based magnetic nanostructures

B. Progress

We developed a novel way to tune the magnetic anisotropy in $(Ga_{1-x},Mn_x)As$ thin films. For this purpose, we made use of a technique called epitaxial lift-off (ELO). Briefly, the $(Ga_{1-x},Mn_x)As$ thin film are first grown lattice-matched on a (001)-oriented GaAs substrate with an intermediate AlAs(60nm) sacrificial layer by means of molecular beam epitaxy. The sample is then covered with wax and immersed into a 7% hydrofluoric acid (HF) solution at 0°C. The very high etching selectivity (~10^8) between AlAs and GaAs, (Ga,Mn)As or (In,Ga)As in diluted HF enables the complete removal of the AlAs sacrificial layer without damaging the upper part of the film; in our case 70nm (Ga,Mn)As layers (S1) or $(In_y,Ga_{1-y})As$ (70nm) / (Ga,Mn)As (70nm) bilayers with y ~ 7% (S2). The layer of interest is then deposited in pure deionized water medium on the new host-substrate. A wide range of substrates may be used in this step. For the present study we limit ourselves to data on [Si/SiO_2(1µm)], but have so far also successfully used InP, BK7 crown glass and (0001)sapphire substrates. After a final bake-out step, Van der Waals bonding keeps the layer fixed onto the host-substrate. The wax can then be removed in a trichloroethylene bath.

Figure 1.3.19 presents how the layers look like after ELO processing. As can be seen, some cracks appear when the deposition step on the host-substrate takes place; they are mostly due to dust trapping in between the layer and the host-substrate (Fig.1.3.18(c)). Despite those defects, millimetric crack-free areas can be achieved and the layer remains well-stuck to the substrate (Fig.1.3.19 (a) and (b)). Temperature-dependent SQUID measurements indicate a Curie temperature (T_C) of 65K for both AG and ELO layers.

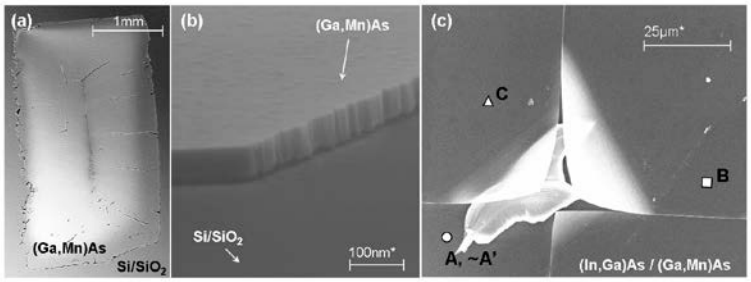


Fig. 3.19. (a) Optical microscope picture of a 70nm (Ga,Mn)As ELO layer. (b) SEM side view of (a). (c) SEM picture of a defect in an (In,Ga)As(70nm)/(Ga,Mn)As(70nm) ELO layer where the layer broke. The labels A(A'), B and C denote specific positions on the sample and are related to the Fig. measurements. In each case, the host-substrate is [Si/SiO_2].

X-Ray Diffraction (XRD) measurements have evidenced the change in the strain conditions in the (Ga,Mn)As layer before and after process. While the as-grown (AG) layers are compressively-strained, ELO S1 is fully relaxed and ELO S2 under a slight tensile strain.

To follow the influence of the (Ga,Mn)As relaxation on its magnetic anisotropy, the layers were characterized applying an external magnetic field perpendicular to the samples planes. We used extraordinary Hall effect (EHE) and polar magneto-optical Kerr effect (P-MOKE) both suited for studying the out-of-plane (OOP) magnetization behavior.

We have developed a reproducible way to tune the magnetic anisotropy in (Ga,Mn)As thin films. Since the layer can be easily detached from its growth substrate this opens the way to research on (Ga,Mn)As in ambient other than GaAs, as our thin films can be transferred to arbitrary substrate materials. Using standard patterning techniques that are well established, the layers can then be patterned into individual nanostructures or array thereof, as demonstrated in Fig. 1.3.20.

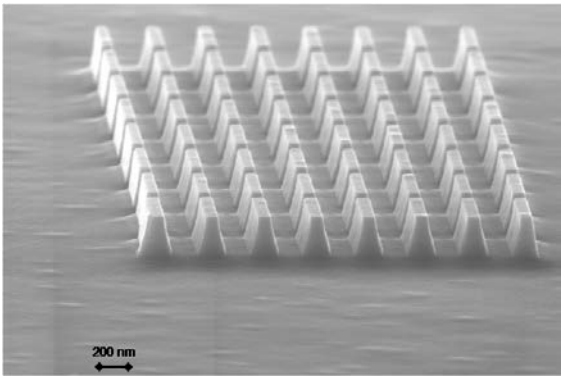


Fig. 1.3.20. SEM image of an e-beam patterned array of (Ga,Mn)As high aspect ratio nanostrucuteres on GaAs.

C. Significant result

- We have developed a novel way of producing (Ga,Mn)As ferromagnetic semiconducting thin films on non-GaAs substrates enabling us to control the strain conditions and thereby the magnetic anisotropies of the film

- We have successful fabricated and characterized GaMnAs nanostructures

D. Critical assessment of the progress

The task has fully reached its goals.

Task 3.3. Structural, magnetic, optical and magneto-optical characterization of the nanostructures

A. Aimed deliverables: To provide characterization of the samples.

B. Progress:

Characterization of the structured GdFeCo samples with the help of X-ray microscopy (PEEM measurements) has a crucial role in the project. In particular, it allowed us to reveal

multidomain structure of elements and inhomogeneity of magnetic anisotropy over a single element.

C. Significant result
Studied structures were very well characterized

D. Critical assessment of the progress
The task has fully reached its goals.

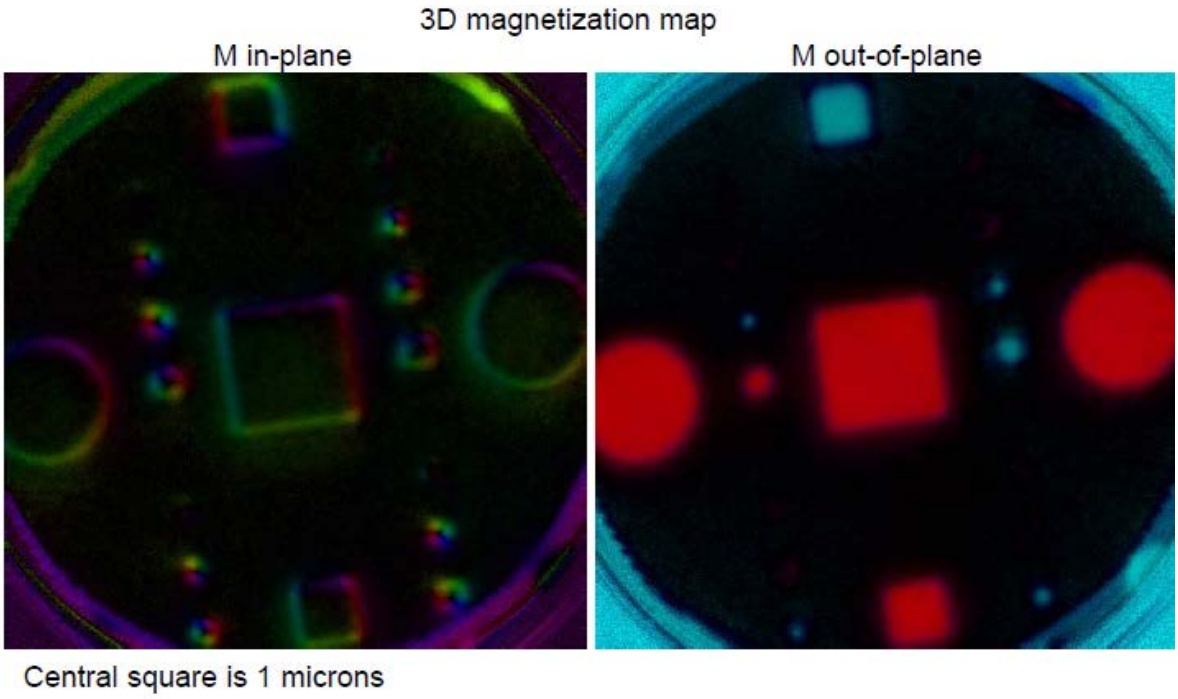


Fig.1.3.21. Magnetic imaging of the structured samples obtained with X-ray PEEM. The Figure reveals inhomogeneities of spin orientation over the structure.

Workpackage 4. Conceptual designs, dissemination and exploitation.
Objectives:

- **initiate developments of novel technologies for unprecedented fast THz magnetic recording and information processing, including spintronics**
- **make concepts for all-optical magnetic recording and optically programmable spintronics device**

A. Aimed deliverables:

- Expert opinion about feasibility and conceptual design of a head and a medium for the ultrafast magnetic recording

- Expert opinion about feasibility and conceptual design of a compact femtosecond laser for the ultrafast magnetic recording and spintronics

- Expert opinion about feasibility and conceptual design of an optically programmable ultrafast spintronics device

B. Progress

Seagate and CEDOVA-Philips have seriously discussed the perspectives of opto-magnetic technology and have made a joint report on this issue suggesting conceptual design for read-head and the required ultrafast semiconductor laser. NXP has changed its strategic product roadmap in the past three years and the spintronic devices are not anymore of interest to them.

C. Significant result

Companies specialized on magnetic recording do consider opto-magnetic technology as a possible way for future development of recording industry. Opto-magnetic recording is on the roadmap of the industry right now.

D. Critical assessment

The task has reached its goals.

1.4 The potential impact and the main dissemination activities and exploitation of results

a) Economical impact

Magnetic recording and processing magnetically stored information is a 30 billion euro per year industry, which, on the one hand, has a huge world-wide market and, on the other, is based and strongly dependent on novel technological concepts. Presently, the speed of one-bit-recording is facing a fundamental and technological gap. Therefore, the search for radically new concepts of ultrafast control of magnetism has become an issue of vital importance for magnetic recording and information processing, including spintronics.

Our project was trying to address the problem of ultrafast control of magnetism and to develop radically new approach for the magnetization reversal using femtosecond laser pulses as a stimulus. The concept goes well beyond state-of-the-art in magnetic storage and information processing technologies. The research results of the project have good chances to deliver a solution to the need for the ever increasing speed of data storage and manipulation as well as to initiate a development of novel technology for unprecedented fast THz magnetic recording and information processing. In particular, the investigated concept of ultrafast laser control of magnetism can be used for switching of nanomagnets in magnetic recording as well as for magnetization reversal in highly polarized spin sources in spintronics, bringing operation speed of both down to a subpicosecond time-domain. Moreover, the laser-generated effective magnetic field investigated in the proposal may be potentially used as an ‘assist’ to ultra-fast switching in current magnetic devices such as write heads. We expect that our project has a very high potential to have a substantial

impact on the enabling technology, such as development of suitable semiconductor lasers. Due to the technology push from the telecommunication industry, there has already been a tremendous development in semiconductor femtosecond lasers with repetition rates approaching the THz range. In parallel, optical telecommunication technology can meet the demands for future bandwidth, but the bottleneck in speed is formed by signal processing. Also here, optical manipulation and processing of information is expected to play an increasingly important role.

We anticipate that the results of the project will help European industry to improve its competitiveness or even help the European companies to obtain world-leading positions by providing a radically new solution to overcome the ultrafast technology gap in magnetic storage and information processing (spintronics)

b) Social and environmental impact

Our project is directly related to one of the major issues in present day information-based society: generation, distribution and storage of an ever increasing amount of information in the form of digital data. Present day developments are not so much facing a capacity and a speed bottleneck, which is directly tackled by our proposal.

Moreover, the increasing amount of data generation, manipulation and transfer has a clear negative side, which is the parallel growth in energy consumption. Magnetism based memories and logic has the great advantage of being non-volatile, that is, information is not lost when power is disconnected. However, the process of magnetization reversal and bits writing remains to be energy consuming. The first experiments have already shown that the laser-induced magnetic switching requires at least 10^3 less energy dissipations than the process of current-induced magnetization reversal. The latter is seriously considered as a possible technology for magnetic writing in future spintronics devices. Therefore, the results of this project may have a positive environmental impact, since magnetic recording and spintronics devices with opto-magnetic writing would require much less energy consumptions than their possible alternatives.

c) Scientific impact

Apart an impact on the modern technology the research was aiming to develop "opto-nano-magnetism" as a new scientific area at the junction of coherent nonlinear optics, nanophotonics and nanomagnetism. Our proposal suggested a pioneering research and aimed to generate breakthrough knowledge in this interdisciplinary area. In our proposal we also aimed to develop novel experimental and computational approaches that will facilitate a radically new view on the ultrafast processes of nanoscale magnetization dynamics. We are happy to claim that scientific results have fully met or sometimes even exceeded our expectations. The consortium has become the absolute leader in fundamental research of ultrafast all-optical magnetic writing. The first results of the research program have been already published in scientific journals of the highest rank including Applied Physics Letters (1 articles), Physical Review Letters (4 articles), Nature-Physics (1 article), Nature (1 article). One manuscript has been recently accepted for Nature Communications. Several manuscripts are still under review. The results of the project have been highlighted in Physics, Nature Photonics, Nature as well as in many national newspapers such as NRC (the Netherlands)

d) Main dissemination activities

The results of the project were disseminated by the partners of the consortium through the following activities

- More than 150 lectures and talks have been given all over the world
- 20 papers have been published only with the duration of the project
- 1 patent is filed
- Several papers summarizing the latest results are still in preparation

Selected dissemination activities are listed below

Patent applications

Patent "Ultrafast heating as a sufficient stimulus for magnetic recording" is in preparation. Details will follow

PhD thesis

Kadir Vahaplar
Title: Novel routes for ultrafast magnetization reversal
Date of defense: 01.09.2011
Promoter: Th. Rasing
Co-promoters: A. V. Kimel, A. Kirilyuk

Addis Mekonnen
Title: Ultrafast laser-induced spin dynamics in GdCo ferromagnetic alloy
Expected date of defense:
Promoter: Th. Rasing
Co-promoters: A. V. Kimel, A. Kirilyuk

Conference contributions

See table 2.

Joint publications

1) K. Vahaplar, A. M. Kalashnikova, A.V. Kimel, D. Hinzke, U. Nowak, R. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing: *Ultrafast Path for Optical Magnetization Reversal via a Strongly Nonequilibrium State,* Phys. Rev. Lett. **103**, 117201 (2009).

2) L. Joly, F. Nolting, A. Kimel, A. Kirilyuk, Th.Rasing, R.V. Pisarev: *Spin-reorientation in the heterostructure Co/SmFeO3*, J. Phys.: Condens. Matter 21, 446004 (2009).

3) J. H. Versluis, A. V. Kimel, A. Kirilyuk, P. Grabs, F. Lehmann, G. Schmidt, L.W. Molenkamp, Th. Rasing, *Electric-field induced modulation of the magneto-optical Kerr effect in a (Zn,Be,Mn)Se/GaAs spintronic device*, Phys. Rev. B **80** 193303 (2009).

4) N. Kazantseva, D. Hinzke, R. W. Chantrell, and U. Nowak: *Linear and elliptical magnetization reversal close to the Curie temperature* Europhys. Lett. **86**, 27006 (2009).

5) T. A. Ostler, R. F. L. Evans, R. W. Chantrell, U. Atxitia, O. Chubykalo-Fesenko, I. Radu, R. Abrudan, F. Radu, A. Tsukamoto, A. Itoh, A. Kirilyuk, Th. Rasing, A. V. Kimel: *Crystallographically amorphous ferrimagnetic alloys: Comparing a localized atomistic spin model with experiments*, Phys. Rev. B **84** 024407 (2011).

6) I. Radu, K. Vahaplar, C. Stamm, T. Kachel, N. Pontius, H. A. Dürr, T. A. Ostler, J. Barker, R. F. L. Evans, R. W. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, Th. Rasing and A. V. Kimel: *Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins.* Nature **472** 205-208 (2011).

7) A. H. M. Reid, G. V. Astakhov, A. V. Kimel, G. M. Schott, W. Ossau, K. Brunner,A. Kirilyuk, L. W. Molenkamp, Th. Rasing*: Single picojoule pulse switching of magnetization in ferromagnetic (Ga,Mn)As,* Appl. Phys. Lett. **97** 232503 (2010).

Other publications

1) G.V. Astakhov, H. Hoffmann, V. L. Korenev, T. Kiessling, J. Schwittek, G. M. Schott, C. Gould, W. Ossau, K. Brunner, and L.W. Molenkamp: *Nonthermal Photocoercivity Effect in a Low-Doped (Ga,Mn)As Ferromagnetic Semiconductor*

2) A. V. Kimel, B. A. Ivanov, R. V. Pisarev, P. A. Usachev, A. Kirilyuk and Th. Rasing: *Inertia-driven spin switching in antiferromagnets,* Nature-Physics **5** 727 (2009).

3) A. Fraile Rodríguez, A. Kleibert, J. Bansmann, A. Voitkans, L. J. Heyderman, and F. Nolting: *Size-Dependent Spin Structures in Iron Nanoparticles*, Phys. Rev. Lett. 104, 127201 (2010).

4) Daniel Steil , Sabine Alebrand, Alexander Hassdenteufel, Mirko Cinchetti and Martin Aeschlimann: *Insights on all-optical magnetization recording by tailoring optical excitation parameters*, accepted at PRB (28.11.2011)

Submitted:

T. A. Ostler, J. Barker, R. F. L. Evans, R. Chantrel1, U. Atxitia, O. Chubykalo-Fesenko, S. El Moussaoui, L. Le Guyader, E. Mengotti, L. J. Heyderman, F. Nolting, A. Tsukamoto, A. Itoh, D. Afanasiev, B. A. Ivanov, A. M. Kalashnikova, K. Vahaplar, J. Mentink, A. Kirilyuk, Th. Rasing and A. V. Kimel: *Ultrafast Heating as a Sufficient Stimulus for Magnetization Reversal in a Ferrimagnet,* submitted to Nature-Communication

Sabine Alebrand , Alexander Hassdenteufel, Daniel Steil, Mirko Cinchetti and Martin Aeschlimann: Interplay of heating and helicity in all-optical switching, submitted to Phys. Rev. Lett.

J.H. Mentink, J. Hellsvik, D.V. Afanasiev, B.A. Ivanov, A. Kirilyuk, A.V. Kimel, O. Eriksson, M.I. Katsnelson, and Th. Rasing, *Ultrafast spin dynamics in multi-sublattice magnets*, submitted to Phys. Rev. Lett.
K. Vahaplar, A. M. Kalashnikova, A.V. Kimel, D. Hinzke, U. Nowak, R. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing, *All-optical magnetization reversal with circularly polarized light: experiment and simulations*, submitted to Phys. Rev. B.

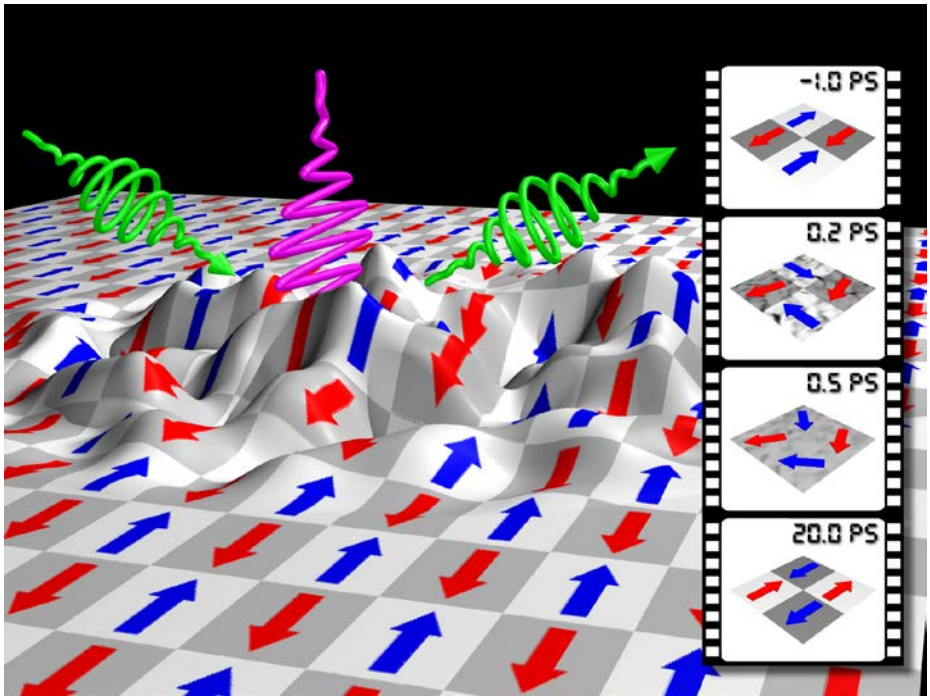
1.5 The address of the project public website

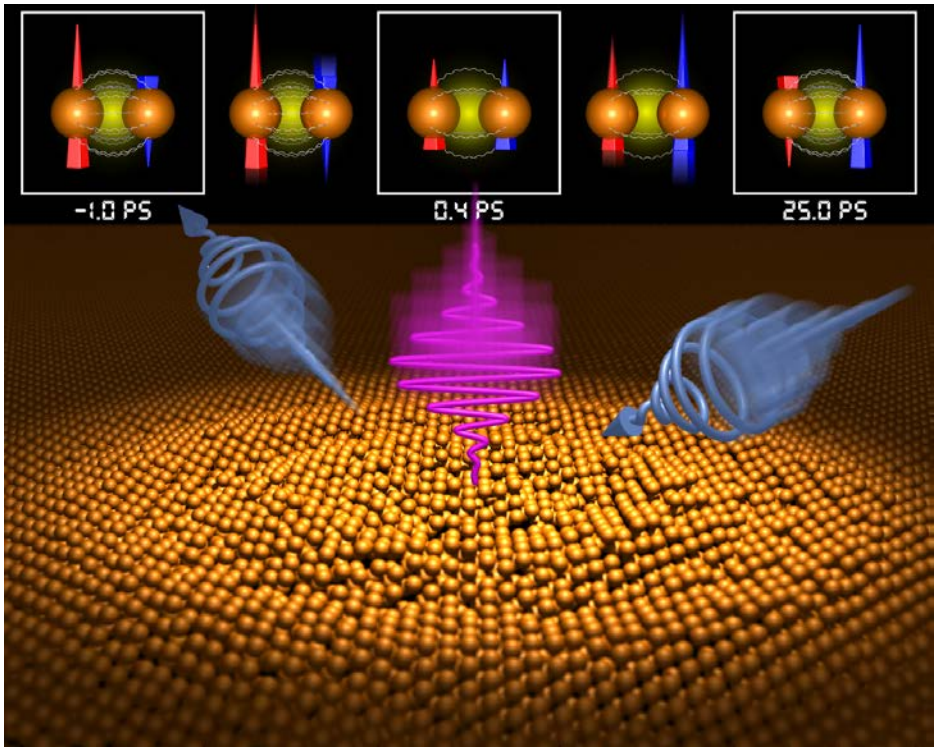
Coordinator: Prof. dr. Th. Rasing
Radboud University Nijmegen, Nijmegen, The Netherlands

Tel.:+31-24-3653141
Fax: +31-24-3652190
Email: th.rasing@science.ru.nl

Project website: http://www.ultramagnetron.org/

1.6 Diagrams and photographs demonstrating and promoting the work





SECTION A. Table A1

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
N	**Title**	**Main author**	**Title of the periodical or the series**	**Number, date or frequency**	**Publisher**	**Place**	**Year**	**Pages**	**Permanent identifiers (if available)**	**Is/Will open access provided to this publication?**
1	Ultrafast Path for Magnetization Reversal via a Strongly Non-equilibrium State	K. Vahaplar	Phys. Rev. Lett.	103	APS	New York	2009	117201		no
2	Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins	I. Radu	Nature	472	NPG		2011	205-208	www.nature.com/doifinder/10.1038/nature09901	No
3	Ultrafast Heating as a Sufficient Stimulus for Magnetization Reversal in a Ferrimagnet, under review with Nature Communications	T. A. Ostler	Nature Communications	Accepted	NPG		Accepted 2011			No
4	All-optical magnetization recording by tailoring optical excitation parameters	D. Steil	Physical Review B		APS		2011			no
5	Ultra-fast spin dynamics: the effect	U. Atxitia	Phys. Rev. Lett.	102	APS	New York	2009	057203		no

	of coloured noise									
6	Linear and elliptical magnetization reversal close to the Curie temperature	N. Kazantseva	Europhys. Lett.	86			2009	27006		no
7	Nanostructuring of GdFeCo thin films for laser induced magnetization switching	L. Le Guyader	Journal of the Magnetics Society of Japan	Accepted			Accepted 2011			No
8	Multiscale modeling of magnetic materials: Temperature-dependence of the exchange stiffness	U. Atxitia	Phys. Rev. B	82	APS	New York	2010	134440		no
9	Spin-reorientation in the heterostructure Co/SmFeO3	L. Joly	J. Phys.: Condens. Matter	21			2009	446004	DOI: 10.1088/0953-8984/21/44/446004	No
10	Size-Dependent Spin Structures in Iron Nanoparticles	A. Fraile Rodriguez	Phys. Rev. Lett	104	APS		2010	127201	DOI: 10.1103/PhysRevLett.104.127201	No
11	In situ contacting and current-injection into samples in photoemission electron microscopes	L. Heyne	Rev. Sci. Instrum.	81			2010	113707	DOI: 10.1063/1.3495967	No
12	Femtosecond Laser Excitation of Spin Resonances in Amorphous Ferrimagnetic Gd(1-x)Co(x) Alloys	A.Mekonnen	Phys. Rev. Lett.	107	APS		2011	117202	DOI: 10.1103/PhysRevLett.107.117202	No
13	Crystallographically amorphous	T. Ostler	Phys. Rev. B	84	APS		2011	024407	DOI: 10.1103/PhysRevB.84.024407	No

	ferrimagnetic alloys: Comparing a localized atomistic spin model with experiments									
14	Single picojoule pulse switching of magnetization in ferromagnetic (Ga,Mn)As	A.H. M. Reid	Appl. Phys. Lett.	97	AIP		2010	232503	DOI: 10.1063/1.3524525	No
15	Ultrafast optical manipulation of magnetic order	A.Kirilyuk	Rev. Mod. Phys.	82	APS		2010	2731-2784	DOI: 10.1103/RevModPhys.82.2731	No
16	Apertureless SNOM study on gold nanoparticles: Experiments and simulations	W.Chen	Physica Status Solidi B	247			2010	2047-2050	DOI: 10.1002/pssb.200983940	No
17	Inertia-driven spin switching in antiferromagnets	A.V.Kimel	Nature-Physics	5	NPG		2009	727-731	DOI: 10.1038/NPHYS1369	No
18	Nonthermal Photocoercivity Effect in a Low-Doped (Ga,Mn)As Ferromagnetic Semiconductor	G. V. Astakhov	Phys. Rev. Lett.	102	APS		2009	187401	DOI: 10.1103/PhysRevLett.102.187401	No
19	Photoinduced Barkhausen Effect in the Ferromagnetic Semiconductor (Ga,Mn)As	G. V. Astakhov	Phys. Rev. Lett.	106	APS		2011	037204	DOI: 10.1103/PhysRevLett.106.037204	No
20	Nonthermal photocoercivity effect in (Ga,Mn)As ferromagnetic semiconductors,	G. V. Astakhov	AIP Conference Proceedings 1399, ICPS30	AIP			2012		To be published	

SECTION A. Table A2

	LIST OF DISSEMINATION ACTIVITIES							
N	**Type of activities**	**Main leader**	**Title**	**Date**	**Place**	**Type of audience**	**Size of audience**	**Countries addressed**
1	Invited seminar	M. Cormier	Addressing magnetism of micro- and nanostructures using far-field optical methods with ultimate space- and time resolutions	March 22, 2010	GEMaC laboratory, Versailles (France)	Scientific Community (Research)		France
2	Invited seminar	M. Cormier	From spin transfer to laser-induced magnetization reversal: towards magnetization control down to the nanometer and picosecond scales	June 10, 2010	Institut Jean Lamour, Nancy (France)	Scientific Community (Research)		France
3	Conference talk	M. Cormier	International Conference on Nanoscale Magnetism: Laser-induced ultrafast magnetization dynamics in a Gd1-xCox ferrimagnetic thin film	September 29, 2010	Istanbul (Turkey)	Scientific Community (Research)		International
4	Invited seminar	M. Cormier	From spin transfer to laser-induced magnetization reversal: towards the control of magnetization down to the nanometer and picosecond scales	January 14, 2011	LCAR laboratory, Toulouse (France)	Scientific Community (Research)		France
5	Invited seminar	M. Cormier	From spin transfer to laser-induced magnetization reversal: towards the control of magnetization down to the nanometer and picosecond scales	March 7, 2011	GEMaC laboratory, Versailles (France)	Scientific Community (Research)		France
6	Conference talk	M. Cormier	Colloque Louis Néel: Laser-induced ultrafast magnetization dynamics in a Gd1-xCox ferrimagnetic thin film	September 22, 2011	Brest (France)	Scientific Community (Research)		France
7	Conference talk	A. Reid	Joint European Magnetism Symposium 2010- Optical access to a forbidden magnetic exchange resonance in lutetium iron garnet	August 23 - 28, 2010	Krakow, Poland	Scientific Community	50-100	International
8	Conference	A. Reid	International Conference on Nanoscale	September	Istanbul, Turkey	Scientific		International

	poster		Magnetism 2010 - Photo Control of Magnetism in a (Ga,Mn)As thin film	28 - October 2, 2010		Community		
9	Conference talk	A. Reid	International workshop on Laser-induced magnetization dynamics in nanostructures - Photo Control of Magnetism in a (Ga,Mn)As thin film	October 3-8, 2010	Stoos, Switzerland	Scientific Community	20-30	International
10	Conference talk	A. Reid	Ultrafast laser control of spins in nanomagnets - Access to a forbidden magnetic resonance using light	October 25-27, 2009	Nijmegen, Netherlands	Scientific Community	30-40	International
11	Conference poster	A. Reid	International Conference on Magnetism 2009 - A new high-frequency magnetic resonance appearing in optical measurements of a doped lutetium iron garnet?	July 26-31, 2009	Karlsruhe, Germany	Scientific Community		International
12	Invited seminar	Th. Rasing	Controlling Magnetism with Light	May 29, 2009.	San Jose	Scientific Community		USA
13	Invited seminar	Th. Rasing	Controlling Magnetism with Light	June 1, 2009	Corvallis	Scientific Community		USA
14	Invited seminar	Th. Rasing	Controlling Magnetism with Light	June 16-18, 2009.	Awaji-island	Scientific Community		Japan
15	Invited seminar	Th. Rasing	Controlling Magnetism with Light	July 1, 2009.	York	Scientific Community		UK
16	Invited seminar	Th. Rasing	Controlling Magnetism with Light	July 3, 2009.	Glasgow	Scientific Community		UK
17	Invited seminar	Th. Rasing	Controlling Magnetism with Light	July 13, 2009	Tohoku	Scientific Community		Japan
18	Invited seminar	Th. Rasing	Controlling Magnetism with Light	July 16, 2009	Tokyo	Scientific Community		Japan
19	Invited seminar	Th. Rasing	Controlling Magnetism with Light	September 20-25, 2009	Nan-Jing, China	Scientific Community		China
20	Invited seminar	Th. Rasing	Controlling Magnetism with Light	September 20-25, 2009	Shanghai, China	Scientific Community		China
21	Invited seminar	Th. Rasing	Controlling Magnetism with Light	September 25, 2009.	Taiwan	Scientific Community		Taiwan
22	Invited seminar	Th. Rasing	Controlling Magnetism with Light	October 15-22, 2009	Colorado Springs	Scientific Community		USA
23	Invited seminar	Th. Rasing	Controlling Magnetism with Light	October 15-22, 2009.	NIST, Boulder	Scientific Community		USA

24	Invited seminar	Th. Rasing	Controlling Magnetism with Light	October 15-22, 2009.	Colorado State University	Scientific Community		USA
25	Invited seminar	Th. Rasing	Controlling Magnetism with Light	October 15-22, 2009.	Chicago	Scientific Community		USA
26	Invited seminar	Th. Rasing	Controlling Magnetism with Light	November 23-27, 2009.	Grenoble	Scientific Community		France
27	Invited seminar	Th. Rasing	Controlling Magnetism with Light	November 23-27, 2009.	Lyon	Scientific Community		France
28	Invited seminar	Th. Rasing	Controlling Magnetism with Light	November 23-27, 2009.	Paris	Scientific Community		France
29	Conference talk		Bliksemsnelle magneten	October 11 (2009).	NEMO Amstredam	Civil Society		The Netherlands
30	Conference talk	Th. Rasing	Optical manipulation of spins	January 8 2010	Spin Workshop Utrecht	Scientific Community		The Netherlands
31	Invited seminar	Th. Rasing	Controllling Magnetism with Light	January 14-15, 2010	FHI Dresden and MPI Berlin	Scientific Community		Germany
32	Invited seminar	Th. Rasing	Controllling Magnetism with Light	January 28-29, 2010	IEEE: Lyon	Scientific Community		France
33	Conference talk	Th. Rasing	manipulation of spins and controlling magnetism with light	March 14-15 2010	APS meeting Portland	Scientific Community		International
34	Invited seminar	Th. Rasing	Controlling magnetism with ligh	March 25-26 2010	Regensburg	Scientific Community		Germany
35	Invited seminar	Th. Rasing	Controlling magnetism with light	April 23 2010	Villigen	Scientific Community		Switzerland
36	Invited seminar	Th. Rasing	Controlling magnetism with light	May 4-5-2010	, LBL Berkeley	Scientific Community		USA
37	Conference talk	Th. Rasing	Controlling magnetism with light	June 12-14 2010	ISIF conference Puerto Rico	Scientific Community		International
38	Invited seminar	Th. Rasing	Controlling magnetism with light	June 23-29 2010	KITPC, Chine Academy of Sciences Beijing	Scientific Community		China
39	Conference talk	Th. Rasing	Controlling magnetism with light	July 12-17 2010	ISAMMA	Scientific Community		International
40	Invited seminar	Th. Rasing	Controlling magnetism with light	September 2 2010	Cambridge	Scientific Community		UK
41	Conference talk	Th. Rasing	Controlling Magnetism With Light	September 20-22 2010	MML	Scientific Community		International

42	Invited seminar	Th. Rasing	Controlling magnetism with light	October 18, 19 2010	University Duisburg/Essen	Scientific Community		Germany
43	Invited seminar	Th. Rasing	Controlling magnetism with light	October 24-26 2010	Nanoguno San Sebastian	Scientific Community		Spain
44	Conference talk	Th. Rasing	Controlling magnetism with light	November 24-25 2010	Nanomagnetisme et spintronique Maison Minatec Grenoble	Scientific Community		France
45	Conference	A. Kirilyuk	1st Korean-Dutch Spintronics Workshop	January 2009	Daejon, South Korea	Scientific Community (Research)	30	International
46	Conference	A. Kirilyuk	International Spin Caloritronics Workshop	February 2009	Leiden, The Netherlands	Scientific Community (Research)	50	International
47	Invited seminar	A. Kirilyuk	Lawrence Berkeley National Laboratory	April 2009	Berkeley, USA	Scientific Community (Research)	30	International
48	Invited seminar	A. Kirilyuk	SLAC National Accelerator Laboratory	April 2009	Stanford, USA	Scientific Community (Research)	30	International
49	Invited seminar	A. Kirilyuk	Georgia Institute of Technology, Atlanta	June 2009	Atlanta, USA	Scientific Community (Research)	30	International
50	Invited seminar	A. Kirilyuk	IBM Almaden Research Center	July 2009	Almaden, USA	Scientific Community (Research)	30	International
51	Invited seminar	A. Kirilyuk	Brookhaven National Laboratory	July 2009	Brookhaven, USA	Scientific Community (Research)	30	International
52	Conference	A. Kirilyuk	Villa Conference on Complex Oxide Heterostructures	September 2009	St. Thomas, US Virgin islands	Scientific Community (Research)	100	International
53	Invited seminar	A. Kirilyuk	Halle/Saale University	November 2009	Halle/Saale, Germany	Scientific Community (Research)	20	International
54	Invited seminar	A. Kirilyuk	Humboldt University	February	Berlin, Germany	Scientific	20	International

				2010		Community (Research)		
55	Invited seminar	A. Kirilyuk	University of Würzburg	May 2010	Würzburg, Germany	Scientific Community (Research)	30	International
56	Invited seminar	A. Kirilyuk	Eidgenössische Technische Hochschule (ETH) Zürich	May 2010	Zürich, Switzerland	Scientific Community (Research)	20	International
57	Conference	A. Kirilyuk	Villa Conference on Complex Oxide Heterostructures	June 2010	Santorini, Greece	Scientific Community (Research)	100	International
58	Conference	A. Kirilyuk	2nd Korean-Dutch Spintronics Workshop	June 2010	Eindhoven, The Netherlands	Scientific Community (Research)	50	International
59	Conference	A. Kirilyuk	JEMS conference	August 2010	Krakow, Poland	Scientific Community (Research)	100	International
60	Conference	A. Kirilyuk	MicroNano Conference	October 2010	Enschede, The Netherlands	Scientific Community (Research)	100	International
61	Invited seminar	A. Kirilyuk	University of Kaiserslautern	November 2010	Kaiserslautern, Germany	Scientific Community (Research)	50	International
62	Conference	A. Kirilyuk	APS March meeting	March 2011	Dallas, TX, USA	Scientific Community (Research)	100	International
63	Conference	A. Kirilyuk	International Workshop Spin Caloritronics	May 2011	Leiden, The Netherlands	Scientific Community (Research)	50	International
64	Conference	A. Kirilyuk	International Workshop “Novel trends in optics and magnetism of nanostructures”	July 2011	Augustow, Poland	Scientific Community (Research)	50	International
65	Conference	A. Kirilyuk	International Workshop “Magnonics: From Fundamentals to Applications”	August 2011	Recife, Brazil	Scientific Community (Research)	100	International
66	Conference	A. Kirilyuk	Moscow International Symposium on Magnetism	August 2011	Moscow, Russia	Scientific Community (Research)	100	International

67	Invited seminar	A. Kirilyuk	The European School on Magnetism "Time-dependent phenomena in Magnetism"	August 2011	Targoviste, Romania		100	International
68	Summer school	A. Kirilyuk	University of Colorado at Colorado Springs	October 2011	Colorado Springs, CO, USA	Scientific Community (Research)	30	International
69	Conference	A. Kirilyuk	International Conference on Magnetism and Magnetic Materials	November 2011	Scottsdale, AZ, USA	Scientific Community (Research)	200	International
70	invited conference talk	U. Nowak	International Symposium on Spin Waves	June 2009	St Petersburg	Scientific Community (Research)	100	all
71	invited conference talk	U. Nowak	International Conference on Superconductivity and Magnetism	April 2010	Antalya	Scientific Community (Research)	50	all
72	invited conference talk	U. Nowak	International Conference on Fine Particle Magnetism	June 2010	Uppsala	Scientific Community (Research)	100	all
73	invited conference talk	U. Nowak	Workshop on quantum effects on ultrashort time scales	May 2011	Leysin	Scientific Community (Research)	50	all
74	invited conference talk	U. Nowak	Magnetic North	June 2011	St John's	Scientific Community (Research)	50	all
75	invited conference talk	U. Nowak	Moscow International Symposium on Magnetism	August 2011	Moscow	Scientific Community (Research)	100	all
76	Presentation	A. Kleibert	SLS Symposium on Magnetism in reduced dimension	3. March 2009	Villigen, Switzerland	Scientific Community (Research)	30	Switzerland
77	Media briefing	F. Nolting	Jahresmedienkonferenz des Paul Scherrer Instituts	23. June 2009	Viligen, Switzerland	Swiss Media	10	Switzerland
78	Conference	F. Nolting	International workshop on Polarized Neutrons and Synchrotron X-rays for Magnetism	August 2. 2009	Bonn	Scientific Community (Research)	100	International
79	Conference	L. Le Guyader	Swiss Workshop on Materials with Novel Electronic Properties	August 2009	Les Diablerets, Switzerland	Scientific Community (Research)	100	Switzerland

80	Conference	F. Nolting	Workshop on Ultrafast laser control of spins in nanomagnets	25. October 2009	Nijmegen, The Netherlands	Scientific Community (Research)	50	International
81	Interview, broadcast	F. Nolting	Radio e Televisiun Rumantscha	26. January 2010	Villigen, Switzerland	Public audience, speaking Rumantscha	Several thousands	Switzerland
82	Conference	L. Le Guyader	Joint European Magnetic Symposia	August 2010	Krakow, Polen	Scientific Community (Research)	200	International
83	Conference	A. Kleibert	International workshop on Laser-induced magnetization dynamics in nanostructures,	6. October 2010	Stoos, Switzerland	Scientific Community (Research)	50	International
84	Conference	L. Heyderman	International workshop on Laser-induced magnetization dynamics in nanostructures,	6. October 2010	Stoos, Switzerland	Scientific Community (Research)	50	International
85	Conference	L. Le Guyader	International workshop on Laser-induced magnetization dynamics in nanostructures,	6. October 2010	Stoos, Switzerland	Scientific Community (Research)	50	International
86	Conference	F. Nolting	Sixteenth Users' Meeting & Workshops NSRRC	21. October 2010	Hsinchu, Taiwan	Scientific Community (Research)	50	Taiwan
87	Presentation	F. Nolting	Physics Department University of Uppsala	2. December 2010	Uppsala, Sweden	Scientific Community (Research)	50	Sweden
88	Conference	F. Nolting	Workshop Nanoscience in the Snow 2011	19. January 2011	Les Diablerets, Switzerland	Scientific Community (Students)	20	Switzerland
89	Presentation	F. Nolting	Physikalisches Kolloquium	23. Mai 2011	Kaiserslautern, Germany	Scientific Community (Research)	50	Germany
90	Conference	L. Le Guyader	Magnetics and Optics Research International Symposium 2011	21. June 2011	Nijmegen, Switzerland	Scientific Community (Research)	200	International
91	Presentations	F. Nolting	Invited talk at SFB668 Colloquium	12. July 2011	Hamburg, Germany	Scientific Community (Research)	50	Germany

92	Conference	L. Le Guyader	workshop Magnetization dynamics in the light of pulsed X-ray sources: From storage rings to X-FELs	28. June 2011	Saint-Aubin , France	Scientific Community (Research)	50	International
93	Conference	F. Nolting	Novel trends in optics and magnetism of nanostructures	5. July 2011	Augustow, Polen	Scientific Community (Research)	100	International
94	Conference	S. El Moussaoui	Novel trends in optics and magnetism of nanostructures	6. July 2011	Augustow, Polen	Scientific Community (Research)	100	International
95	Presentation	F. Nolting	Physikalisches Kolloquium	23. Mai 2011	Kaiserslautern, Germany	Scientific Community (Research)	50	Germany
96	Conference	L. Le Guyader	Moscow International Symposium on Magnetism	21. August 2011	Moscow, Russian	Scientific Community (Research)	100	International
97	Conference	S. El Souliman	Workshop on X-Ray View of Ultrafast Dynamics in Solids	29. November 2011	Berlin, Germany	Scientific Community (Research)	50	International
98	conference	M. Aeschlimann	Conference on surface plasmon photonics SPP4		Amsterdam	Scientific community (research)		international
99	workshop	S.Alebrand O. Schmitt A. Hassdenteufel	UltraMagnetron workshop Nijmegen	25.10.2009-29.10.2009	Nijmegen	Scientific community (research)		
100	seminar	D. Steil	WEH-seminar	11.2009	Ringberg	Scientific community (research)		international
101	Conference	M. Aeschlimann	OSA: Photonic Metamaterials and Plasmonics Topical Meeting	07.06.2010-09.06.2010	Tucson	Scientific community (research)		international
102	workshop	P.Haak	International workshop “Energy Dissipation at Surfaces”	05.09.2010-08.09.2010	Schöntal	Scientific community (research)		international
103	workshop	M. Cinchetti	SEPnet Workshop	13.09.2010-14.09.2010	London	Scientific community (research)		UK (europe)
104	Conference	A. Hassdenteufel	Frühjahrstagung der deutschen physikalischen Gesellschaft (DPG)	21.03.2010-26.03.2010	Regensburg	Scientific community		Germany

						(research)		
105	Workshop (participation, no presentation)	S. Alebrand	UltraMagnetron Workshop Stoos	3.10.2010-8.10.2010	Stoos	Scientific community (research)		
106	Conference	M.Aeschlimann	Symposium für Mikrostrukturphysik	01.12.2010	Halle	Scientifiy community (research)		international
107	conference	S. Alebrand A. Hassdenteufel D. Steil	Frühjahrstagung der deutschen physikalischen Gesellschaft (DPG)	13.3.2011-18.3.2011	Dresden	Scientifiy community (research)		Germany
108	Conference	M.Aeschlimann	ElePSI	29.05.2011-01.06.2011	Bad Staffelstein	Scientific community (research)		international
109	conference	D. Steil	MORIS	21.6. 2011.-24.6. 2011	Nijmegen	Scientific community (research)		international
110	conference	S. Alebrand	MMM conference	30.10.2011-3.11.2011	Scottsdale/Arizona	Scientific community (research)		international
111	Conference	A. V. Kimel	New Light Source Project, Condensed Matter Workshop	21st May 2008	Rutherford Appleton Laboratory, Didcot,	Scientific community (research		international
112	Conference	A. V. Kimel	PhD Network Workshop "Photons and Matter	29 June - 4 July 2008	2008 d'Amelander Kaap, Hollum, Ameland	Scientific community (research		international
113	Conference	A. V. Kimel	Joint European Symposia on Magnetism	September 14-19 2008	Dublin	Scientific community (research		international
114	Conference	A. V. Kimel	3rd International Conference on Photo-Induced Phase Transitions and Cooperative Phenomena (PIPT2008)	November 10, 2008	Osaka	Scientific community (research		international
115	Presentation	A. V. Kimel	University of Yokohama	January 16, 2009	Yokohama	Scientific community (research		Japan
116	Presentation	A. V. Kimel	Nihon University	June 2 – 4, 2009	Tokyo,	Scientific community (research		Japan

117	Conference	A. V. Kimel	International workshop on the Spectroscopy and Coherent Scattering Endstation and associated instrumentation at the European XFEL	June 7-12 2009	Villigen	Scientific community (research		international
118	Conference	A. V. Kimel	International Symposium Spin Waves	July 20-24 2009	St. Petersburg	Scientific community (research		international
119	Conference	A. V. Kimel	International Colloquium on Magnetic Films and Surfaces ICMFS2009	August 2-7 2009	Berlin	Scientific community (research		international
120	Conference	A. V. Kimel	International Workshop “Magnonics: From Fundamentals to Applications”	October 2009	Dresden	Scientific community (research		international
121	Conference	A. V. Kimel	European Synchrotron Radiation Facility	January 2010	Grenoble	Scientific community (research		international
122	Conference	A. V. Kimel	Joint Conference INTERMAG-MMM	March 2010	Washington	Scientific community (research		international
123	Presentation	A. V. Kimel	University of Versalles	March 2010	Versalles	Scientific community (research		France
124	Presentation	A. V. Kimel	University of Porto	June 2010	Porto	Scientific community (research		France
125	Presentation	A. V. Kimel	University of Vienna	September 28 - October 2, 2010	Vienna	Scientific community (research		France
126	Conference	A. V. Kimel	International Conference on Nanoscale Magnetism ICNM-2010	October 2010	Istanbul	Scientific community (research		international
127	Presentation	A. V. Kimel	University of Exeter	October 19 2011	Exeter	Scientific community (research		UK
128	Presentation	A. V. Kimel	Nihon University	October 18 2011	Chiba	Scientific community (research		Japan
129	Presentation	A. V. Kimel	Nihon University	June 28-July	Chiba	Scientific		Japan

				2 2011		community (research		
130	Conference	A. V. Kimel	International Conference on Photo-Induced Phase Transitions PIPT-2011	March 20-March 25 2011	Wroclaw	Scientific community (research		international
131	Conference \	A. V. Kimel	March Meeting of American Physical Society	April 29 2011	Dallas	Scientific community (research		international
132	Conference	A. V. Kimel	National Seminar Condensed Matter Physics 2011	July 2-July 7, 2011	Nijmegen	Scientific community (research		The Netherlands
133	Interview	P6	Focus: A light touch, Phys. Rev. Focus 23, 15	May 8, 2009	N. A.	Scientific Community (Research)	N. A.	worldwide
134	Workshop	P6	Photomagnetism in (Ga,Mn)As ferromagnetic semiconductor, Radboud University Nijmegen	October 29,	Nijmegen	Scientific Community (Research)	30	The Netherlands
135	Conference	P6	Nonthermal photocoercivity effect in (Ga,Mn)As ferromagnetic semiconductors, 30th International Conference on the Physics of Semiconductors	2009	Seoul	Scientific Community (Research)	200	South Korea
136	Conference	P6	Nonthermal photocoercivity effect in ferromagnetic semiconductors, 6th International Conference on the Physics and Applications of Spin Related Phenomena in Semiconductors	July 27, 2010	Tokyo	Scientific Community (Research)	50	Japan
137	Publication	P6	Spin optics in Mn-doped GaAs	August 2, 2010	N. A.	Scientific Community (Research)	N. A.	worldwide
138	Colloquium	P6	Johannes Kepler University of Linz	January 18, 2011	Kaiserslautern	Scientific Community (Research)	20	Germany
139	Conference	P6	Nonthermal photocoercivity effect in (Ga,Mn)As ferromagnetic semiconductors, Magnetics and Optics Research International Symposium	March 10, 2011	Taipeh	Scientific Community (Research)	50	Taiwan
140	Colloquium	P6	Photomagnetism of diluted magnetic semiconductors, Workshop on Novel Trends	April 26, 2011	St.Petersburg	Scientific Community	20	Russia

			in Magnetism of Nanostructures			(Research)		
141	Colloquium	P6	Photomagnetism in (Ga,Mn)As ferromagnetic semiconductor, Moscow International Symposium on Magnetism Lomonosov State University	2011	Linz	Scientific Community (Research)	20	Austria
142	Conference	P6	Nonthermal photocoercivity effect in (Ga,Mn)As ferromagnetic semiconductors, Graduiertenkolleg 792, Technische Universitaet Kaiserlautern	June 7, 2011	Nijmegen	Scientific Community (Research)	150	The Netherlands
143	Workshop	P6	Magnetic anisotropy in lifted-off (Ga,Mn)As thin films, IEEE International Magnetics Conference	July, 2011	Augustow	Scientific Community (Research)	40	Poland
144	Conference	P6	Photocoercivity effect in (Ga,Mn)As ferromagnetic semiconductors, Ioffe Physical-Technical Institute	2011	Moscow	Scientific Community (Research)	150	Russia
145	Interview for newspaper	A.Kimel	NRC-Next: Ongelooflijk snelle magneten	April 2, 2011	The Netherlands	Public community	Several thousands	The Netherlands