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All-optical switching in Co/Pt magnetic dots

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All-optical switching in Co/Pt magnetic dots

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Abstract

In the field of ultrafast magnetization dynamics it is recently shown that it is possible to get all optical switching (AOS) in Pt/Co/Pt layers with femtosecond laser pulses. AOS promises a new future in traditional data storage devices, where data is written completely optically thus increasing the speed of these storage devices. Thus far it is believed that AOS in Pt/Co/Pt can only be achieved with multiple pulses, where the first laser pulse always creates a multidomain state. In this study a method is devised to achieve single pulse AOS.

For this method dots are created which are the size of the magnetic domains found in multidomain states. The idea behind this is that in each dot only one magnetic domain can be found, then there has to be some sort of complete switching inside of each dot. The dot structure is made using lithography, where the, electronbeam dose, dot size and distance between dots is varied. These dots are first characterized with external magnetic fields, before the real AOS is investigated.

In this study the variable in the dots are measured using the magneto-optic Kerr effect (MOKE) in the Kerr microscope. There is found to be switching in all the different dots, visible by hysteresis loops and Kerr images. The dots switch nucleation based, meaning each dot has a slightly different switching field. When investigating this switching further, there is found to be an effect of the dipole fields, which is statistically substantiated.

Single pulse laser experiments are then done, where is found that most dots still have multidomain states inside of them, but also some complete single pulse AOS is found.
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Chapter 1

Introduction

In our everyday society the role of the computer cannot be underestimated and a large part of the computer is the ability to store and retrieve information. The first developments in the world of hard drives started in the 1950s [1]. Back then people could buy a RAMAC (Random Access Method of Accounting and Control), which was the size of about two refrigerators and could store 5 MB. Over the years the storage devices have been greatly improved in storage amount, size, speed and efficiency, but since the last couple of years the improvement is slowly stagnating[2]. The increase in storage density is mainly accomplished by decreasing the bit sizes, but this cannot go on forever. This is due to something called the magnetic recording trilemma [3]. This trilemma states that a trade-off is needed between thermal stability, writability and signal-to-noise ratio. The signal-to-noise radio cannot be decreased further, because nowadays this is already at its limit, reduce the signal and it is not possible to measure something at all. That is why it is now a trade-off between writability and thermal stability. If the magnetic bits become too small the thermal energy is already enough to magnetically switch the bits, meaning they become thermally unstable. The stability could be improved by increasing the magnetic anisotropy, but this in turn makes it harder to switch the bits and thus resulting in a lower writability. The hard disk drives (HDD) nowadays write data by a small magnetic field applied by a writing head, but these fields are not large enough to switch these bits. It seems this is where the traditional HDDs limits lay.

Heat-assisted magnetic recording (HAMR) is an example of a new technology which tries to overcome this problem. HAMR focusses on a new way of writing data, which is able to switch bits even with a very high coercivity[2]. This is done be using a laser to locally heat the bit that is being written. The laser reduces the magnetization and thus allows the external magnetic field to switch the bit. This technology thus only focuses on increasing storage density, by reducing the bits-size below the thermal stability limit for HDDs.

It should be even better if the writing speed could also be improved. The speed at which magnetic bits are written with magnetic fields is in the order of nanoseconds. One way to improve this speed is using light instead of a current generating a magnetic field. This light, which is in the form of the laser can influence the magnetization on a lot smaller timescale, in the range of picoseconds[4]. So if the switching is done all optically the speed could drastically increase. Recent studies have shown the first steps in this all-optical switching(AOS).

The paper that lays at the basis of AOS was already published in 1996 by Beaupaire et al.[4]. It showed it was possible to get ultrafast demagnetization in the picosecond timescale
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Figure 1.1: The ultrafast demagnetization of NiMgF$_2$ causes by an intense femtosecond laser pulse. Image taken from [4].

by using an intense femtosecond laser pulse, as can be seen in figure 1.1. The discovery that the magnetization can be manipulated by heating is not all surprising, but that it happens at this timescale was not expected by the physical models at that time. This in turn let to an increase in research on the subject of ultrafast magnetization dynamics. In this field the goal is to determine what the driving mechanism is behind these ultrafast dynamics, but even today there is no agreement over what these mechanisms are.

In 2007 it was discovered that it was possible to switch magnetization in GdFeCo with only femtosecond laser pulses[5]. First was thought that the AOS in GdFeCo was dependent on the polarization of the laser, but later it was discovered by Radu et al. that the switching was similar for all polarizations[6]. This was explained by the lattice structure of the GdFeCo, which is a ferrimagnet. This means GdFeCo has a double lattice with opposites magnetic moments (Gd and Fe), these magnetic moments have a different switching time, resulting in a complete switch if a laser pulse fully demagnetizes the GdFeCo. So if one laser pulse can fully demagnetize the GdFeCo, single pulse AOS is possible. This single pulse AOS can be seen in figure 1.2a, where for the three polarizations the same result is seen. The first pulse completely switched the magnetization and the second pulse completely switches the magnetization back. For a more detailed explanation one is referred to [6].

In 2014 there was discovered that AOS was also possible in Pt/Co layers[8]. There is a large difference between Pt/Co and GdFeCo in the lattice structure, because Pt/Co has only one material and thus one magnetization, so the switching principle of Pt/Co is also not the same as GdFeCo. The switching is explained as a combination of two mechanisms, at first there is the ultrafast magnetization by absorbing the energy of the laser, then secondly by exposure to an external magnetic field the magnetization will tend to align in the same direction. This external magnetic field is believed to be caused by the inverse Faraday effect(IFE), which states that circular polarized light induces a magnetization in a material according to the direction of the polarization. The IFE is believed to be strong enough to eventually switch the Pt/Co fully, but there is little proof that single pulse AOS is possible. The AOS switching
Figure 1.2: AOS for (a) GdFeCo and (b) Pt/Co/Pt. (a) The AOS in GdFeCo for a left circular, right circular and linear polarized laser, where in shot 2, a second laser pulse is shot on the same spot. (b) The AOS in Pt/Co/Pt also for left circular, right circular and linear polarized light, where the second laser pulse is shot at the same spot. Both images taken from [7].

In this report a study for the possibility of single pulse AOS in Pt/Co layers is performed. Before single pulse studies are done, first the behavior of the switching is characterized with external applied fields, then the switching behavior with single laser pulses is investigated. After that there will be investigated if complete single pulse switching is possible, which has never been proven. This is done by creating small magnetic dots, the size of single magnetic domains. Normally after a single laser pulse a multi domain state is formed, but if the magnetic dots are as small as the magnetic domains, no multi domain state can form in such a dot (the magnetic island is simply to small). So what will happen if you expose such a magnetic dot to a laser.
Chapter 2

Theoretical background

In this chapter a theoretical background is given for this study. First a basis concerning magnetism is discussed. Then the importance of magnetic anisotropy and magnetic domains will be shortly mentioned. After that AOS will be more thoroughly explained, because this effect stands at the core of this study. Lastly the dipole effect will be discussed.

2.1 Magnetism

In this study Pt/Co layers are used, which are ferromagnets. The total magnetic energy density is described by 2.1 and the most likely magnetic state is found at the minimum of the magnetic energy\[9\],

$$U = \int_{V} \left( \frac{A}{|M|^2} (\nabla M)^2 - \mu_0 M \cdot H_{ext} - \frac{\mu_0}{2} H_d \cdot M + K \sin \theta^2 \right) dV. \quad (2.1)$$

These 4 terms thus determine the magnetic state. This first term determines the exchange energy of the system, where $A$ represent the exchange stiffness and $M$ the magnetization. The exchange energy is minimized when spins align, because these aligned spins have their electrons further away from each other resulting in a lower energy according to the Pauli principle. The second term in 2.1 is because of the Zeeman effect. The Zeeman effect states that the spins align with the external magnetic field, $H_{ext}$, where $\mu_0$ is the vacuum permeability. These first two terms together assume an isotropic material, meaning the magnetization is independent of the direction. The shape dependence (anisotropy) is introduced with the last two terms. The third term is the demagnetization energy, which is minimal when the stray fields are minimized. Which is when the magnetic spins align along the longest axis of the sample, in the thin film samples used this is the in-plane direction. Here $H_d$ is the demagnetization field. Finally the last term which tends to align the spins along a certain easy axis, here $K$ is an anisotropy constant, which simply depends on the material used and $\theta$ the angle between this easy axis and $M$. These last two terms can be combined for thin film samples into[9],

$$K_{eff} = K - \frac{1}{2} N_z \mu_0 M_s^2, \quad (2.2)$$

where the $K$ again stands for the anisotropy constant which for thin film is in the out-ofplane direction, but this gets partly compensated by the second term, which is the demagnetization term, with $N_z$ is the shape factor and $M_s$ is the saturation magnetization, which is the
maximum magnetization and stands in the in-plane direction. There is thus a competition between in-plane and out-of-plane magnetization.

2.2 Magnetic anisotropy

There are two types of anisotropy: volume anisotropy and interface anisotropy. This combined anisotropy prefers the spins to be aligned in a certain way and along a certain axis, the so-called easy axis, which is the energetically favorable axis. The interface anisotropy has its main cause in spin-orbit coupling, which states that the magnetic spin is coupled to the orbit motion of the electrons. This effect is the strongest on the interface between two materials. The volume anisotropy on the other hand originates in the dipole fields [9]. These two types of anisotropy compete as follows [9],

\[ K = K_V + \frac{2}{t} K_S, \]

(2.3)

here \( t \) represents the thickness of the sample. \( K_V \) is determined by volume anisotropy and has its easy axis in-plane. While \( K_S \) is determined by the spin-orbit coupling and has its easy axis out-of-plane. In bulk materials the volume anisotropy dominates, resulting in a dominantly in-plane magnetization, while for thin-film materials the surface anisotropy dominates resulting in a dominantly out-of-plane magnetization. This can also be seen in equation 2.3, if the magnetic sample (in this case the Co layer) becomes thicker the second term in 2.3 becomes smaller and the \( K_V \) will dominate, resulting in in-plane magnetization. Out-of-plane magnetization is found for Co thicknesses of \( 0.6 \text{nm} < t < 1.5 \text{nm} \) [8].

In figure 2.1 the behaviour of the magnetic layers versus the applied magnetic field can be seen, figure 2.1a for an in-plane magnetization and figure 2.1b for out-of-plane magnetization. The behaviour of the out-of-plane magnetization is characterized by a hysteresis loop, because the path is dependent on the starting point. So from negative field and magnetization to positive field and magnetization gives a different path than vice versa. For the thin film samples used, the abrupt change from a negative to a positive magnetization or the other way around corresponds with the magnetic switch in the sample. There is thus a range of fields where the magnetization can be either up or down depending on the starting point. This field is called the coercive field or the switching field. When the out-of-plane anisotropy is higher it costs more energy to switch the sample and the coercive field also increases. The in-plane figure has no hysteresis behaviour and thus also no coercive field, another way to compare in-plane with out-of-plane is remanence. The remanence is the normalized difference between magnetization at zero field and the saturation magnetization, the remanence of the out-of-plane hysteresis loop is thus 100%, while the in-plane hysteresis loop has a 0% remanence. For a clear magnetic switch a high remanence is thus necessary, meaning a thin layer structure is most suitable.
2.3 Magnetic domains

The thin film samples made in this study all have some inhomogeneities, for example lattice impurities, edges, interface effects etc. The perpendicular magnetic anisotropy (PMA) at these inhomogeneities is lowered in comparison with the rest of the sample, which results in faster switching at these points, called nucleation sites. A magnetic domain is thus created due to nucleation. The edges of these domains are called domain walls, here the magnetization switches from up to down. These magnetic domains then expands across the sample when a parallel magnetic field to the domain is applied. This expansion can be driven by two principles: nucleation and propagation, this can be seen schematically in figure 2.2, where in figure 2.2a a single magnetic domain can be seen and in 2.2b the difference between propagation dominated(top) and nucleation dominated(bottom).

Propagation dominated means an extend of the domain wall starting at a nucleation points until the whole sample is switched, this occurs in a short time. Complete switching occurs thus not long after a a nucleation point switches, meaning the coercive field is dominated by the switching of a nucleation point.

The nucleation dominated process on the other hand is a fairly slow effect and this is often caused by domain wall pinning or in the case of this study by making a dot structure. When increasing the magnetic field more nucleation points pop up, until the whole sample is again switched[10]. For more information about domain wall pinning the reader is referred to [9].
2.4 All optical switching

In this part a short explanation of the AOS is given, which is already briefly mentioned in the introduction. As mentioned before, the mechanism behind AOS is not completely unravelled by scientists yet, especially for the Pt/Co layers. There are two mechanisms believed to be potentially responsible for this switching. The first one is the Inverse Faraday effect (IFE), this states that polarized light induces a magnetization in a magnetic material, which has the same effect as a small applied field, where left and right circular polarized light induces an opposite magnetization. So when a laser pulse is shot on a sample, the first pulse only causes demagnetization, independent of polarization. After full demagnetization has occurred, a multidomain state is formed. In such a state there are roughly 50% up domains and 50% down domains. A subsequent polarized laser pulse then increases either the up domains or the down domains dependent on the polarization of the laser. So multiple pulses are necessary to achieve full switching. In 2016 a deeper study was done into the number of pulses necessary to achieve AOS in Pt/Co [7]. In this study Hall bars were used to measure magnetization time, where the influence of independent pulses is studied. This effect can be seen in figure 2.3. In figure 2.3a it is shown that multiple pulses (independent of helicity) are necessary to first achieve full demagnetization. After full demagnetization it is shown in 2.3b that again multiple pulses (dependent of helicity) are necessary to achieve full switching.

The second potential mechanism is Magnetic circular dichroism (MCD), this is a fairly complex effect. Here only a small introduction to MCD is given, for more in-depth information one is referred to [11]. This effect states that right circular and left circular polarized light has different refractive indices and thus also different absorption for both polarizations. The amount of energy absorbed by the sample depends thus on this polarization. The MCD study done by Khorsant et al. only studied GdFeCo, where switching is possible only due to the amount of heat absorbed, so helicity independent. This is not the case with Pt/Co, where there is only found helicity dependent switching [11]. So it is not yet clear what MCD means for Pt/Co.

Regardless of which mechanism is the driving force behind the switching, it is clear that single pulse AOS is not yet found. In this study a possible solution is investigated to get
single pulse AOS. As mentioned before the first pulse always creates a multidomain state. In this multidomain state, multiple up and down states are formed, these states have a certain domain size. The average domain size can be altered by changing the thickness of the Co layer, where a decrease in the thickness of Co, increases the average domain size[8]. The idea is to then make a dot structure, where each dot is smaller than the average domain size and thus in each dot only one domain can exist. If then a laser is shot at the sample, the magnetization in a dot can either stay the same or completely switch, it is hoped that a circular polarization is then enough to either switch the dot or keep the dot in the same magnetic state, dependent on the direction of circular polarized light. At least a multidomain state can thus not exist in a single dot.

2.5 Dipole fields

As discussed in section 2.4 a dot structure might prove an answer to single pulse AOS. This dot structure can be seen as multiple magnetic point charges, which affect each other through dipole fields. This is an important effect, because this could mean the dots do not switch independently. A schematic view of dipole fields are given in figure 2.4. The magnetic bit A has a magnetic influence on bit B, because of this dipole field the preferred state of bit B is in the opposite direction of the original bit. This effect is only strengthened by the dipole field of bit C on B. The dipole field thus prefer the magnetic states to be in a checkerboard pattern; up and down alternating.

This dipole field can be calculated with[12],

$$B_B = \frac{\mu_0 m}{4\pi r^3}. \quad (2.4)$$

Here $m$ represent the magnetization of the bit and $r$ the distance from the a point to point $B$. Because of the $\frac{1}{r^3}$ dependence, the dipole effect of bit $A$ onto bit $C$ is very small, so only nearest neighbours give a contribution to each other.
Figure 2.4: A representation of three 2D magnetic bits, where the dipole field of the three bits are shown with the blue arrows outside of the bits. The red bits stand for a up magnetization, while the blue bit stands for a down magnetization.
Chapter 3
Experimental set-up

In this chapter the experimental set-up will be explained. First the sample production and the structure will be explained, then the basic principle of magneto-optic Kerr effect (MOKE) will be explained, followed by the applied MOKE principles in the static MOKE set-up and in the Kerr microscopy. Lastly the laser set-up will be elaborated.

3.1 Sample production

The samples used in this study are made with a DC sputtering process in ultra high vacuum, which can be seen in figure 3.1. This sputtering process is started by inserting an argon gas into the vacuum chamber, this argon gas is ignited into a plasma by applying a high voltage between the ring and the target. The argon gas is then accelerated against the target, where the energy of the argon atoms is enough to release atoms from the target. This target is made from the atoms that are to be sputtered. The released atoms then have a chance to condensate to the substrate and form the grown sample. The precision of this process is extremely high, it can be done with sub-nanometer precision[13].

Lastly also lithography is used for making the dot structure, as mentioned in section 2.4. Lithography is schematically described in figure 3.2 and 3.3, where it is split between the lithography processes and the sputter deposition after. The first step in lithography is spin coating a masking layer, PMMA (3.2 step 1), where the PMMA consist of long polymer chains. The next step is choosing what kind of structure is desired, in this case this should be the dot structure, which will be further elaborated on in section 3.2. After choosing the appropriate structure it has to be written in the masking layer, this is done by an electron beam (3.2 step 2). The electron beam damages the masking layers, destroying the polymer chains, making the irradiated part weaker, visualized as the red area in 3.2 step 2. The developer, MIBK, is then applied, where only the part where the polymers are damaged dissolves. After the developer with the destroyed parts of the PMMA is cleaned, all that is left is a negative image of the desired structure, seen in 3.2 step 3. The next step is to sputter the appropriated material on the sample, this can schematically be seen in figure 3.3 step 5. Then the last task is to remove the remaining mask (including the layers on top of the mask), which is done with acetone. All that is left is the substrate and on the desired places the Pt/Co layers (3.3 step 6), in this case thus a dot structure.
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Figure 3.1: A schematic view of the sputter deposition. In this vacuum chamber an argon plasma is ignited and used to release atoms from the target material onto the substrate. Image taken from [14].

Figure 3.2: A schematic view of the steps taken in a lithography process. (1) A masking layer is spin coated across the sample. (2) The desired place for the final structure are irradiated with an electron beam, destroying the PMMA. (3) These damaged parts of PMMA are then removed by a developer and what is left is a negative of the desired structure. Image taken from [15].

Figure 3.3: A schematic view of the steps taken after the lithography process. (4) The same structure as in 3.2 step 3 is prepared for sputtering. (5) Onto the whole sample the appropriate layers are sputtered. (6) The remaining masking layer with the layers on top is wiped away with acetone, resulting the desired structure. Image taken from [15].

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3.2 Sample structure

The samples grown by sputter deposition and lithography will be discussed in this section. All samples have a SiB substrate, because of the strong thermal conductivity of this substrate, on which Ta(4nm)/Pt(4nm)/Co(Xnm)/Pt(4nm) is grown, with a Co thickness X of 1nm and 8nm. These thicknesses are chosen in the range of perpendicular magnetic anisotropy (PMA), as described in 2.2. The first layer of Ta is used, because it promotes proper growth for the layers on top, which ultimately creates a more homogeneous sample. The Pt layers are used for a good interface with the Co, because of their strong spin orbit coupling. The top Pt layer also functions as protective layer for the Co against oxidation. For the creating of the dot structure again Ta/Pt/Co/Pt is sputtered with a Co thickness of 0.8nm, where the structure is made using Lithography. The reason for using 0.8nm Co will be discussed in section 4.1. The dot structure which is created by this process is partly shown in figure 3.4. Every square seen in the image is an array of circular dots of different sizes and which different distances between the dots. The different dot diameters are 800nm, 1000nm and 2000nm, respectively for the left column, middle column and right column. While the different distances between the center of the dots are six, four and three times its radius, respectively for the top, middle and bottom row. This result in a three by three grid where every array of dots is different in size and distant between dots. Every array is 300\(\mu\text{m}\) by 300\(\mu\text{m}\) in size with a distance of 600\(\mu\text{m}\) between each array. All this information is also written with the electron beam under each array as can be barely seen in figure 3.4, here also a magnification of a dot array is shown. Each structure of three by three arrays as discussed above, is repeated four times across the sample. In these 4 structures the electron beam doses is also varied, there is experimented

Figure 3.4: An optical microscope picture of a part of the dot structure. All the different dot configuration for an electron beam dose of 900\(\frac{\mu\text{C}}{\text{cm}^2}\), where the second smaller image is a magnification of the 2000nm three times distance dots.
with a dose of 800, 900, 1000 and 1100 µC/cm². So figure 3.4 is repeated four times each with a different dose. From this point onwards the dots will be referred to as diameter with \( x \) times distance, e.g. 2000nm with three times distance, meaning the 2000nm dots with three times the radius as distance between centers.

### 3.3 Magneto Optic Kerr Effect

In this section the basic principles of MOKE are discussed, after that the applied uses MOKE are discussed, Kerr microscopy and static MOKE. The measurements done in this study are all done based on the Magneto Optic Kerr Effect (MOKE). The easiest way to see this effect is when comparing it with the Faraday effect, where the polarization of light is slightly altered when it reflects off a magnetic surface.

Linear polarization consists of both left-circular and right-circular in equal amplitudes, but which are both differently absorbed by the magnetic material. This results in reflected light with a certain change in ellipticity and change in rotation, the Kerr ellipticity and the Kerr rotation. The change in polarization is a measure for the local magnetization, so if two perpendicular polarizers are placed, before and after reflection, only the Kerr reflection is transmitted. Which makes it able to measure magnetization. The MOKE principle is schematically seen in figure 3.5, where linear polarized light reflects off a magnetic surface, resulting in elliptic polarized light.

The MOKE principle can be used to measure in-plane and out-of-plane magnetization. In this study only samples with PMA are used, so the only interest is in the out-of-plane set-up. The effectiveness of this set-up can be improved if the light travels with a small angle of incident. How the MOKE is used in the measurements will be discussed in section 3.3.1 and 3.3.2. For a more detailed explanation see [13].

![Figure 3.5: A schematic view of the MOKE principle, linear polarized light reflects on a magnetic surface, resulting in a change in rotation and ellipticity. Image taken from [16].](image)

### 3.3.1 Kerr microscope

For the characterization of the switching dots and thin films the Kerr microscope is essential. With the Kerr microscope one is able to see the magnetization of the sample in real-time.

The Kerr microscope is a combined microscope with polarization optics, so that simultaneously the normal microscope image and the MOKE image can be seen. In this microscope
the objective lenses can be changed and the field of view is between \( \sim \text{cm} \) and \( \sim 10\mu\text{m} \). The resolution is limited by the diffraction limit, which makes 500nm structures resolvable. This limit can further be improved by oil immersion and special lenses. The Kerr microscope further uses a CDD camera, with a typical frame rate of 16 fps. This frame rate decreases when a higher shutter time is needed for more light onto the sample, which is needed with higher magnifications. The Kerr microscope is schematically shown in figure 3.6. The lamp used is a high intensity Xenon arc lamp which shines through the diaphragm, which is set into the polar MOKE mode, where the diaphragm is a centered square. Then the light passes a polarizer after which it gets focuses onto the sample. After reflection the light travels through a compensator, which separate the polarizations of the light. Then the light travels through an analyzer, which is a combined perpendicular polarizer and removes the ellipticity and analyzes it before it can be seen with the camera. What is left is an intensity mainly determine by the change in polarization due to the MOKE principle. This intensity will be recorded by the CCD and can be tuned by the user, changing contrast, background subtraction and other processing tools. This results in a greyscale live image with darker and lighter areas represent up and down magnetization. To see any change in magnetization a magnet is used to change the magnetic field in the out-of-plane direction. For the dot measurements later in this study a hysteresis tool is used, where certain regions of interest can be chosen to measure a local hysteresis loop.

### 3.3.2 Static MOKE

The static MOKE set-up is also briefly used in this study. This set-up, as seen in figure 3.7, relies on the same principles as the Kerr microscope, but without being able to see the real-time magnetization, so only hysteresis loops can be measured.

A laser passes through a polarizer, gets focused on the sample, reflects through the second perpendicular polarizer and lands in the detector. Here again the change in polarization is
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a measure for the magnetization according to the MOKE principles. In the static MOKE set-up a PEM and lock-in amplifier are used to improve the signal-to-noise ratio. In short the PEM gives the laser signal a certain frequency, which gets compared in the lock-in with the signal of the detector, which has the same frequency. The part of the signal of the detector which does not oscillates on the same frequency of the PEM can then be identified as noise and can be filtered out. The static MOKE is thus used to get improved hysteresis loops, for a more detailed explanation about this set-up one is referred to [17].

![Figure 3.7: Schematic view of the static MOKE set-up, a laser passes through a polarizer, PEM, lens and onto the sample. After reflection the laser pulse passes through another perpendicular polarizer and lands in the detector, where the signal of the PEM and the detector are combined to increase the signal-to-noise ratio. Image obtained from [17].](image)

### 3.4 Laser set-up

The last set-up used in this study is the laser set-up, shown in figure 3.8. This set-up is used to shoot femtosecond laser pulses onto the sample. First this pulse passes a neutral density filter (ND filter), this an continuous intensity filter which is used tune the intensity between zero and maximum intensity. Then the laser passes a shutter, which can be opened and closed electronically. A beam splitter is then used to make sure the laser can pass through the center of the lens, the beam splitter then divides the laser pulse into a part which passes through the beam splitter and a part which gets reflected of the beam splitter (the dotted line in 3.8). This pulse is focused onto the sample by the lens after which it gets reflected back through the lens and because of the beam splitter this pulse then gets reflected to the detector.

These pulses have to land very precisely onto the sample, therefor the sample is placed on a sample holder which is attached to three motors, controlling the x,y and z position very accurately.

A typical measurement would go as follows. First the sample is placed in the sample holder, then a calibration of the position of the dots has to be done. The dots are found by doing line scans across the surface, where the dots have an other reflection then the non magnetic substrate in between the arrays of dots. When the exact position of the right array of dots is known, the measurement can commence. First the sample has to be completely saturated in one direction. Then with help of the shutter exactly one pulse has to hit the correct spot on the sample. After that the sample will be slightly moved and the process is repeated. If all the desired pulses have been shot, the sample can be removed and investigated in the Kerr microscope.
Figure 3.8: Schematic view of the laser set-up, the laser pulse first travels through a ND filter, then a shutter, after which a beam splitter makes it possible to go through the middle of the lens. The laser pulse is then focused onto the sample, after which it gets reflected, again the pulse then travels through the lens and gets reflected of the beam splitter to the detector. Here the dotted line represent the reflection of the beam splitter which is not used.
Chapter 4

Results and discussion

In this chapter the result of this study will be showed. First some result on the 1nm and 0.8nm Co samples are shown, which is done to have reference measurements for the dots. Then the results of the dots will be shown, these consist of: variation of dose, size, some edge effects and lastly the laser experiment.

4.1 Switching characterization

The first step in determining if single pulse AOS is possible is to have a reference of how the thin film samples behave: how does the switching take place, what are the reactions after a single pulse laser pulse etc. So first the 1nm and 0.8nm Co samples are tested for their general characterization by measuring their hysteresis loops. Which is done in the static MOKE set-up as discussed in section 3.3.2. Here an external magnet is used to apply a field from -100mT to 100mT, where the hysteresis loops for both samples can be seen in figure 4.1.

![Hysteresis loop of 1nm Co sample](image1)

![Hysteresis loop of 0.8nm Co sample](image2)

Figure 4.1: (a)The hysteresis loop of the 1nm Co sample. (b)The hysteresis loop of the 0.8nm Co sample.

These hysteresis loops both have a remanence of 100% and thus prove a PMA material. The coercive field are for both the same, from -20 mT to 20 mT. One would expect the
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switching field to differ slightly for different samples of PMA Co material. This because the thicker Co sample has a lower anisotropy, meaning it should be easier to switch it, but as explained in section 2.3 a nucleation point always occurs at a defect. For these thin film samples the switching is propagation dominated, meaning the coercive field is determined by the nucleation point. If both of the samples have nucleation points which switch at the same field, this would explain the similarity of the coercive field.

Besides the hysteresis loops, a reference for the Kerr microscope is also needed. Typically such an image looks like figure 4.2. Here a domain wall is shown by increasing the magnetic field until a nucleation point forms, after which the domain propagates across the sample. When then the magnetic field is turned off, the domain wall will stop moving and the image is taken. Here again propagation dominated switching can thus be seen.

Figure 4.2: A domain wall of the 1nm Co sample, where the darker part represents an up magnetization and the lighter part a down magnetization.

The last experiment done with these thin film Co samples are single shot laser measurements. Here according to section 3.4 multiple single shot laser pulses are shot on the sample, each on a different spot on the surface. As expected a multidomain state is then created, because it is the most energetic favorable state. The size of the area which is affected depends on the laser intensity, where the minimum intensity to get any switching with is found to be 8mJ/cm², see appendix .1.

Furthermore when comparing the results of the 1nm Co and the 0.8nm Co sample there is found to be indeed a multidomain size dependence on the thickness of the Co, as stated by Lambert et al. [8]. The multi domain state created by the single pulse has a certain domain size, which increases when decreasing the thickness of the sample Co layer. This is because the Energy of a domain wall scales with an exchange variable and an anisotropy constant via [16],

$$E_{dw} = 4\sqrt{AK_{eff}}. \quad (4.1)$$

If the thickness decreases the anisotropy, $K_{eff}$ increases while the exchange constant, $A$, stays the same, so the energy of the domain wall, $E_{dw}$ also increases. The more energy a domain wall cost the less domain walls will be presents and thus the larger the domain sizes. The
Kerr image of these multidomain states can be seen in figure 4.3, where 4.3a is for the 0.8nm Co sample and 4.3b for the 1nm Co sample.

Figure 4.3: The multidomain state achieved by a single linear polarized laser pulse for (a) the 0.8nm Co sample and (b) the 1nm Co sample.

The average multidomain state for the 0.8nm sample is about 2 \( \mu \text{m} \), while the 1nm sample has a domain size \(<1\mu\text{m}\). This is an important finding for the dot structure. The magnetic domain size should be as large as possible to ensure only one magnetic domain can exist in a single dot. For that reason the 0.8nm sample is used for making these dots.

### 4.2 Dots characterization

The configuration of the dots can be seen in section 3.2. There are thus 4 different doses and the first step is to determine which is the ideal dose. Therefore the first test done is determine if they is a different between these doses.

#### 4.2.1 Dose comparison

The dose represent how long the electronbeam irradiates at a certain spot. If the dose is too low, the PMMA material is not damaged enough resulting in leftover material after the acetone is used to remove the PMMA. When the material is then sputtered onto the sample, the areas with leftover PMMA get an uneven growth of the layers and thus these part have less PMA. On the other hand, when the dose is too high too much of the PMMA is removed, so not only the programmed dots but also area outside of the dots gets effected. If that is the case the programmed structure is lost and in the worst case the dots are such a size the begin to link up with each other.

The doses used here are 800, 900, 1000 and 1100 \( \mu \text{C/cm}^2 \). For the purpose of investigating if there is an effect for the different doses, the doses of 800 and 1100 \( \mu \text{C/cm}^2 \) are compared. First the optical microscope is used to determine if it is possible to see defects in the dots due to dose mismatch. A comparison of these two doses for the same dots (2000nm three times distance) in the optical microscope can be seen in figure 4.4, where (a) has a dose of 800 \( \mu \text{C/cm}^2 \) and (b) has
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a dose of 1100 $\mu C/cm^2$. In this figure no difference between the doses can be seen, this is because the resolution of the optical microscope falls short. A way to improve the resolution enough to see inside of the dot structure is using a scanning electron microscope, which will be able to determine if any defects are inside the dots.

For further determining of the dose effect different dots have been selected across a certain dose plus diameter and on these dot hysteresis loops are measured. Some of these curves can be seen in figure 4.5. Here only half of the hysteresis curve is shown, the reason for that will be explained in section 4.2.2, where a more in-depth study in the switching characterizations is done.

Here the left column has a dose of 800 $\mu C/cm^2$ and the right of 1100 $\mu C/cm^2$, furthermore is the top row for the 1000nm dots with three times distance and the bottom row for 2000nm dots also with a three times distance. There are a couple of effects which have to be explained, first of all the saturation of the Kerr intensity. The Kerr microscope has a maximum of intensity which it can measure. When this maximum is almost reached, an increase of magnetic field will not give a linear amount of Kerr intensity, which result in an asymptotic behavior. This asymptotic behavior then translates to an non-linear increase when the linear background is subtracted. This effect is also what is seen in most of the graphs in figure 4.5 for the higher magnetic fields. This effect is thus not due to a dose mismatch. Secondly linear drift is a problem in these measurements, linear drift originates in the sample simply moving, for instance through vibrations in the building. Then the regions of interest selected (the regions were the hysteresis loops are being measured) also move, resulting in a mismatch, so more linear background is being measured if the region of interest moves and thus encompasses a larger area outside of the dot. The result of this can be seen in 4.5d, where the front and the backswep have a different slope, thus creating a divergent graph. Normally when measuring a complete hysteresis loop this can be compensated by making sure the begin and end point are the same point, thus removing the divergence. Both the linear drift as the asymptotic behavior are not relevant for this study.

Now comparing the result of both doses no significant differences can be seen, because
every dot is already different, making it hard to say what the origin is of the seen differences. One difference is that the 800 \( \mu \text{C/cm}^2 \) dose seems to have a little bit more uncertainty mainly for the 2000nm dots, but even this effect can be ascribed to many other effects. Such as sub-optimal settings in focus and contrast or simple to small an area chosen for the hysteresis curve. Even if this effect is because of the dose, the effect itself is already not noticeable by the 1000nm dots. From all this the conclusion is made that the different doses are all within the range of the perfect dose. So for further experiment a middle ground is chosen at the dose of 1000.

### 4.2.2 Switching dots

Having determined what the proper dose is, now will be looked properly into the switching. What already is shown in figure 4.5 is that there is indeed proper switching for these dots.
Though these hysteresis curves do not have the same PMA behaviour as seen with the thin film samples in figure 4.1. This is easily explained when considering the dots have only a very small area when compared to the thin film and thus a lower signal. Also to get the dots in focus a very high magnification is used, but even then the dots are not completely in focus. The smaller the dots the less they are in focus and the lower the signal-to-noise ratio, plus the effect that the smaller dots have an even smaller area and smaller signal. The signal-to-noise ratio is already improved by measuring only half of a hysteresis loop, as also seen in figure 4.5. When measuring only half a background subtraction can be chosen at a higher field, 20mT. With such a subtraction all the background noise at this field will be removed, resulting in a better signal-to-noise ratio around this field. If the difference between the background subtraction and the actual field becomes larger, the signal-to-noise ratio becomes worse. For this reason only in a small region of fields (half of the hysteresis loop) can be measured if using the background subtraction. These hysteresis curves can be seen for all the different sizes in figure 4.6, where a, b and c are for the 800nm three times distance, 1000nm four times distance and 2000nm six times distances respectively and d is for multiple dots of 2000nm with three times distance.

![Graphs of hysteresis curves](image)

Figure 4.6: Half of hysteresis curves for dots of (a) 800nm with three times distance, (b) 1000nm with a four times distance, (c) 2000nm with six times distance and (d) the hysteresis curves for multiple 2000nm three times distance dots.
Again some linear drift and saturation effects are found in 4.6, but these are again not important for this study. The 800nm closest distance dots have been chosen, because these are the hardest dots to measure, while the 2000nm dots with the largest distance have been chosen, because they are the easiest to measure. Here the 1000nm dots provide a middle ground between the two.

What one would expect is that the signal to noise ratio decreases by decreasing dot size, simply because there is less signal in a smaller dot. This trend indeed seems to hold when comparing the graphs in figure 4.6a, b and c, where the 800nm dots clearly have the least clear switch and the 2000nm dots have the best signal-to-noise ratio. In figure 4.6d multiple switching 2000nm dots are shown, here it is clearly seen that each dot does not have the same switching field. This is as expected when considering that dots have nucleation driven domain wall motion (2.3). A domain wall in a dot is isolated from the other dots, so each dot must have a nucleation point inside before switching can happen. Switching at these nucleation points occurs at different fields, the strong defects switch easier than the weaker defects. The switching range of the 2000nm dots is statistically calculated at 32.0mT with a standard deviation of 0.7mT and for the 1000nm dots this range of fields is calculated at 29.9mT with a standard deviation of 0.6mT. The 800nm dots are also measured, but because the low resolution of the Kerr microscope no reliable data can obtained. The coercive field of the larger dots is thus higher, this is not as expected. The dots are larger, therefor there is also a higher possibility of defects inside, making it easier for switching to occur. While there is no real reason why the larger dots have a higher switching field.

There is also a difference in switching field between the thin film samples en the dot structure, where the dot have a higher switching field. This can be explained, because the switching in thin films is propagation dominated while the dots have nucleation dominated switching, as discussed in section 2.3.

![Figure 4.7: A Kerr microscope image from the (a)2000nm four times distance dots and (b)2000nm three times distance dots. Both images taken where not all dots have switched yet.](image)

The switching thus indeed occurs for different dots. The next step is to make the switching process visible with the Kerr microscope, this is seen in figure 4.7, where two partly switched
arrays are shown with different magnifications and dots. Here the lighter contrast represents already switched dots and the darker contrast dot which have not yet switched. One interesting finding is in the way the dots switch. In figure 4.7a there are switched dot formation as predicted in section 2.5, where altering up and down magnetic states are formed, the checkerboard pattern. Apart from these predicted formation, also dot formations that cannot be explained with dipole fields can be seen, neighboring dots with the same magnetization. There is thus more explanation necessary then only the dipole fields, which is again these nucleation points. In a checkerboard dot formation, a dot which should not switch according to the dipole fields, can easily switch because of a nucleation point present inside of the dot. The following questions then arise: How strong is this dipole field?, Which of these effects dominate or is it all just randomness?. The only real way to figure this out, is making a statistical analysis of partly switched arrays, as seen in figure 4.7.

4.2.3 Statistical Analysis

In this section the statistical analysis discussed in 4.2.2 is done. Here partly switched arrays of dots are investigated for the effect the dipole field play. For this statistical analysis a new variable has to be introduced the ”checkerboardness” denotes as CB, this is a measure for the effect the dipole fields have on the switched dots. The CB is calculated for each dot individually, a schematic view of such a calculation can be seen in figure 4.8a, here the red and blue dots represent opposite magnetizations.

![Diagram](image.png)

Figure 4.8: (a) A schematic view of nine dots and how checkerboardness (CB) is calculated for the middle dot, where the blue and red dots represent a opposite magnetization. Each neighbor with a parallel magnetization has a -1 contribution and each anti parallel neighbor has a +1 contribution. (b) The graph of the checkerboardness of randomly switched dots versus the amount of dots switched(filling).

In this figure only the CB of the middle dot is calculated, where each neighboring dot with a parallel magnetization contributes a -1 and each neighboring dot with an anti-parallel magnetization contributes +1. So if all the neighboring dots have an anti-parallel magnetization the Cb is +4 and represent a full checkerboard pattern and all parallel neighbors represent a -4 and no checkboard at all. The CB is then summed over all the measured dots, after it is normalized to range from -1 to +1. A 1 thus represent a full checkerboard pattern and a
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-1 represent no checkerboard at all. Note that a full checkerboard pattern can only occur if half of the dots are switched and no checkerboard occurs if the dots are fully switched and if there is no switching at all.

This measured value is then compared with a simulation of a randomly filled array of dots of the same size, with roughly the same amount of switched dots. The behaviour of the randomly generator simulation is shown in figure 4.8b, where the filling (fraction of dots switched) is plotted versus the normalized checkerboardness. In the figure can be seen that with zero filling and with full filling there is a CB of -1 and with half a filling there is a CB of zero, because there are randomly as many dots up as down.

![Graph](image)

Figure 4.9: (a) The graph of the statistical analysis of 2000nm four times distance dots, where the normalized checkerboardness (a measure for the effect of the dipole field) is plotted versus the percentage filling. The black data point are the random measurements and the red dot is the measured value. (b) The graph of the statistical analysis of 2000nm three times distance dots, with the red data point the measured value and the black data point the random values. Here three plotted lines are shown, where the middle black line is the average of the random data points, the bottom green line the average minus the standard deviation and the top pink line the average plus the standard deviation.

The CB of the simulation is then compared with CB of an image taken of a partly switched array, which is shown in figure 4.9, the black squares represent the randomly generated values from the simulation and the red square represent the measured value. This is done for the 2000nm four times distance and the 2000nm three times distance dots, respectively for 4.9a and 4.9b. For the four times distance dots the red square can be seen inside of the cloud of black dots, meaning there is no significant difference between the measured value and randomly switched dots. For the three times distance the red square is found outside of the cloud of black squares, so here might be a dipole effect present, here the dipole effect has to be stronger, because of the $\frac{1}{r^3}$ behaviour of the dipole field as found in 2.5. This is further investigated with the three plotted lines, here the middle black line represent the trend found in figure 4.8b, which is estimated as a linear fit through the data point, because of the small range of filling when compared to the general trend. Then the standard deviation of the is calculated after subtracting this linear fit. The top and bottom linear lines are then the linear fit plus-minus the standard deviation. So now it is clear the measured value falls way outside
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the standard deviation and thus there can be concluded that the dipole field play a role in the switching of the 2000nm three times distance dots.

The question then arises how great this effect is for different distances between the dots and in what range of filling the dipole fields play a role. For reliable answer on these questions a more extended statistical research has to be done. This then has to be done with a program which can automatically calculate the CB of a Kerr image of partly switched arrays, because doing this by hand as these two analyses are done would take to much time. Then the amount of filling has to be varied across a range of 0-100% filling, which will gives some answer about the maximum dipole effect and by which filling this occurs. This also has to be done for different dot sizes and distances, after which reliable conclusion can made about the effects of the dipole fields.

4.2.4 Edge effects

An interesting effect is found at the edge of each array of dots. When increasing the magnetic field the most outer rows of dots have roughly the same low coercive field, this can be seen in figure 4.10. Here two followings images have been made with the Kerr microscope with an increasing magnetic field, 32mT and 34mT respectively. For both fields not all the dots have switched yet, with more dots switched for the higher field. In this figure the effects at the edge (top-left) can be compared with what happens at the middle of an array (bottom-right). One can see that the edge indeed has the most switching, while the middle switches as discussed in section 4.2.2.

![Figure 4.10: Kerr images from the edge of an array of 2000nm dots with 3 times distance for different magnetic field, (a) a magnetic field of 32mT and (b) a magnetic field of 34mT. Both figures are taken at the top-left of the array.](image)

The effect at the outer rows on the other hand can not be explained with the previous knowledge about dipole fields. The amount of outer rows which behave oddly is depended on the magnetic field, where with a lower field also less rows are effected, in figure 4.10a only the first outer row seems to be effected, with an exception at the top-left corner where roughly the first five rows seems effected. In the second figure, 4.10b, around five outer rows have
almost completely switched, where in the middle less than half of the dots are switched. One possible explanation could lie in the way the dots are made with lithography. When a certain dot is being written also the neighboring dots are affected with undesired radiation, weakening the masking layer. This results in an increased doses for the dots, but because the outer rows have less neighboring dots, they also get a lower doses. A lower doses means a dot with a higher chance of having a defect and thus a nucleation point, which in turn makes the dots easier to switch. Although this is a possible explanation, in section 4.2.1 it is stated that there is not noticeable difference between a dose of 800 and 1100. The different in dose due to its neighboring dots is expected to be much less and so also not such a large difference is expected at the edge as seen here.

4.2.5 laser characterization

In this last section the effects of a single linear polarized femtosecond laser pulse are investigated. Therefore the laser set-up as described in section 3.4 is used, after which the sample is investigated in the Kerr microscope. To then get an image it is necessary to take a background and use the external magnet to induce a change, because only a change relative to the background can be made visible.

The sample is first saturated in the up direction, after which the laser switches some dots in the down direction. Then in the Kerr microscope a magnet field is applied in the up direction, therefore the dots that are switched by the laser, will switch back again, making them visible with the Kerr microscope. I.e. the dots that were switched by the laser are the only dots which will not show any change when applying the magnetic field. This means that an image is created, where the changed dots have been switched by the laser, while the unchanged dots are not affected by the laser. The effects of a laser pulse can be seen in figure 4.11, where the magnetic field is 10mT, 20mT and 60mT respectively for a, b and c. Here another unexpected result can be seen, when looking at 4.11a and b. These have been made at magnetic fields of 10mT and 20mT, but the first switching does not occurs until around 28mT. One would thus expect to see nothing when increasing the field, because the dots that have not been switched by the laser should only switch at a higher field, meaning they have not changed yet and meaning one would expect an image where everything has the same dark contrast. Still there is found to be a lot of change when applying these lower fields, that is why there is already so much light contrast in figure 4.11a.

When increasing the field from 10mT to 20mT even more change is detected, when again there should be none. Finally when the field is increased to 60mT (4.11c) all the dots are saturated in the up direction, so every dot that has the lighter contrast is switched by the laser. One would expect a multi domain state across the dots after a linear polarized laser pulse, i.e. about half of the dots should be in the up state and half of dots in the down state, which is clearly not the case here.

So it is quite odd that with field of 10mT already a change is seen and that after saturating the dots more than half of the dots seem to be switched by the laser. Still a plausible explanation has to be with the size of the dots. The dots used are the 2000nm three times distance, because these dots are the best when it comes to taking clear Kerr images. Originally these 2000nm dots were chosen in the dot structure, because the average domain size of 0.8nm Co is about 2000nm, see 4.1. Now it seems this domain size is smaller than expected, when comparing it with the thin film 0.8 nm Co sample. If there are indeed multidomain states inside of the dots, it would explain the behavior found. A multidomain state inside of the...
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Figure 4.11: Kerr images after a single femtosecond linear polarized laser pulse of an array of 2000nm dots with 3 times distance for different magnetic field, (a) a magnetic field of 10mT, (b) a magnetic field of 20mT and (c) a magnetic field of 60mT. All images are taken from the same spot on the sample.

dot would react even to low magnetic fields. This domain state then grows through domain
wall motion into the direction of the magnetic field. Meaning the changes seen in figure 4.11a are due to multidomain states expanding until the edges of the dot. The magnetization that changes is then made visible as a light contrast, while the other direction stays the same dark contrast. This can be seen in figure 4.11a and b, where some dots seem to be about half dark and half light.

The multidomain states also explain that in figure 4.11c there are so little dark dots. Only the dots which are completely unaffected by the laser appear completely dark. On the other hand the dots that appear completely light are then also completely switched by the laser. This complete switching is substantiated with the difference between figure 4.11b and c, there are dots which appear completely dark in the second image but are completely light in the last image. These dots are then completely switch by the laser. It thus seems there is some single pulse AOS but mostly there are still multidomain states inside of the 2000nm dots, but this is only one measurement so for a more reliable conclusion more measurements have to be done.

Another conclusion found is that because of the multidomain states inside the dots nothing relies can be said about the influence of the dipole fields as predicted by 4.2.3. With the previous knowledge of the 2000nm three times distance dots one would expect to see more of a checkerboard pattern, but because of the multidomain states the dipole fields are completely shifted. A dot which consist of half up, half down already has minimized dipole fields. On top of that because of the multidomain states it is hard to say what the original state after single pulse AOS was.

The dots thus switch somewhat as expected, when accounting for possible multidomain states inside of the dots. But it is also clear there is no completely single pulse AOS for these dots, but there seem to be some individual dots which do switch completely.

To improve the study in the effect of single pulse laser pulse, measurements for smaller dots have to be done, making sure no multidomain states occur inside of a dot. For these smaller dots also the resolution should be increased, because there were already difficulties with making clear Kerr microscope images of the 1000nm dots. A way to do this is oil immersion with special optics in combination with the Kerr microscope or magnetic force microscopy(MFM), which has a better resolution. A disadvantage of MFM is that only a small sample can be inserted and it takes a longer time to create such a image. If there is a certainty only a single magnetic domain can occur in a dot, helicity dependent can also be measured and there can be made a conclusion if single pulse AOS is indeed possible.
Chapter 5

Conclusions and outlook

In this study the possibility for single pulse all optical switching (AOS) in Pt/Co is investigated. Therefore a dot structure is eventually made, with the idea that when the domain sizes are larger than the size of a magnetic dot, only one magnetic state can occupy one dot. This then could result in one laser pulse completely switching a dot. Before the dots can be investigated, first some more general characterization about AOS have been made with two thin film Pt/Co/Pt samples with Co thicknesses of 0.8nm and 1nm.

From these samples first off hysteresis loops are made, this is done to have a reference of the thin film samples to compare with the dots. The switching fields of the thin films are both found to be -20mT and 20mT After this the first characterization of a single laser pulse is made, this result in a multidomain state for a linear polarized laser. The size of these multidomain state is found to be depending on the thickness of the Co layer, where the 1nm Co samples is found to have a domain size of $<1\mu$m and the 0.8nm Co samples has a domain size estimated on 2$\mu$m. If the thickness of the Co thus increases the domain size decreases.

With lithography the dot sample is then made. The thickness of the Co is chosen at 0.8nm, because a large domain size is necessary to have a single domain state in a dot. Therefor the size of the dots have as largest diameter 2000nm, the estimated size of a domain, with the remaining dot sizes at a diameter of 1000nm and 800nm. Here a trade-off has to be made between signal to noise ratio and the size dots. The smaller dots are harder to measure, but here it is more likely only one domain state fits in a single dot.

On this dot sample apart from the size also the distance between dots and the electron-beam dose is varied. The different distances are used to find any effects of dipole field, where the closest distance between dots have the highest dipole field and highest dipole interaction. The variation in dose is used to experiment what the proper electronbeam dose is, too low and there are still remnants of the masking layer when sputtering the sample, resulting in defects. Too high a dose will result in too much of the masking layer being removed resulting in a not proper defined dot structure. After measuring the hysteresis loops of various dot sizes and distances for different doses, there is found no real difference in signal to noise ratio for the various doses of 800, 900, 1000 and 1100 $\mu$C cm$^{-2}$. Therefor a middle ground is chosen and the remaining measurements are done with the dose of 1000 $\mu$C cm$^{-2}$.

Then the switching of the different dot sizes is more closely investigated. Here is found
the 800nm dots are too small to get very reliable data. It is clear there is magnetic switching for all the dot sizes, which are all measured using magnetic fields. The switching is also made visible with Kerr microscope images, but because the Kerr microscope used does not have a high enough resolution, the 800nm dots are always out of focus. The 2000nm and 1000nm dots both show magnetic switching under influence of an external magnetic field, but because the 2000nm have the clearest image, these are chosen for the later laser measurements.

From these Kerr images, especially the ones where only a small amount of dots have switched, the switching characterizations become a bit more clear. The switching begins the same as in thin film, with a dot with a (large) defect inside, but because the dots are not linked to each other the magnetic domain cannot spread to neighbouring dots. The next dots to switch is then determined partly by the dipole field and partly by more (lesser) defects. This result in a progress of switching where most of the switched dots are neighboured by dots of an opposite magnetization, similar as a chessboard pattern. This is also statistically investigated, where is found that there is indeed a dipole preferred switching in the 2000nm dots with a three times distance. There is also found that there is no dipole switching for the 2000nm four times distance dots.

Then some interesting findings at the edge of an array of dots are determined, where the outer rows are the first to completely switch when increasing the magnetic field. Also the amount of rows which are affected by this unknown effect increases with increasing magnetic field. The only explanation for this effect is that the outer rows get less of a electronbeam dose. This is because the electronbeam also irradiates neighbouring dots, beside the dot which is currently being written. Then because the outer rows have less neighbouring dots, the dots also get a lower dose. Although this is an explanation, this is not considered to be the driving force behind this, because this decrease in dose should be very small, lower than the difference in doses of the arrays. There is found to be no noticeable difference between these large dose difference, so also no difference is expected because of the small decrease in dose.

Lastly single pulse AOS is investigated by shooting a femtosecond linear polarized laser pulse on the dot structure. Here is found that the 2000nm dots still have multidomain states inside of (most of) the dots. Therefore no complete single pulse all optical switching is found, but there are found to be some individual dots which do seem to switch completely. To reliably determine if there is single pulse AOS is possible more measurements have to be done. These measurement should thus be done with the smaller dots, preferably with the dots of 800nm or even smaller. To measure these dots also the Kerr microscope resolution has to be improved, with for example with oil immersion in combination with special optics or magnetic force microscopy. Then the result of a single laser pulse on dots with only one magnetic domain can be determined and can be established if using small dots is a solution for getting single pulse AOS.
Bibliography


laser measurements on 0.8nm Co samples

Here the series of laser measurements depended on laser intensities is shown.

Figure 1: Single pulse laser shot with different intensities for the 0.8nm sample, where every multidomain state is an effect from a single laser pulse.