High frequency magnetic field sensors

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Faculty of Physical Sciences
University of Iceland
2016
HIGH FREQUENCY MAGNETIC FIELD SENSORS

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60 ECTS thesis submitted in partial fulfillment of a Magister Scientiarum degree in Engineering Physics

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Reykjavik, June 2016
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Hall effect in Fe-Pt and anisotropy in Ni-Fe
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Bibliographic information:
Egill Ingi Jacobsen, 2016, High frequency magnetic field sensors, M.Sc. thesis, Faculty of Physical Sciences, University of Iceland.

Printing: Háskólaprent, Fálkagata 2, 107 Reykjavík
Reykjavik, Iceland, June 2016
Abstract

This thesis presents the results of two independent studies. The first study is focused around the anomalous Hall effect in Fe\textsubscript{x}Pt\textsubscript{1−x} thin films. The anomalous Hall voltage is measured while the sample passes an alternating current through it. This is done at a few different frequencies. It turns out that the anomalous Hall voltage oscillates, in each measurement, with the same frequency as the current. The power of those frequencies remains constant for frequencies below 123.7 kHz, but above that the power starts to drop dramatically. This is believed to be caused by limitations in the FePt samples, rather than limiting factors of the anomalous Hall effect. The second study is focused around the magnetic anisotropy of Ni\textsubscript{81}Fe\textsubscript{19}. The anisotropy is measured in films of different thicknesses. From that data the surface anisotropy constant in the films is evaluated as $K_s = (8\pm2) \times 10^{-4}$ erg/cm\textsuperscript{2}. It is also concluded that for thicknesses above 100 nm the films are considered bulk with an anisotropy constant of $K_u = 1440 \pm 120$ erg/cm\textsuperscript{3}. The anisotropy constant of NiFe films was also measured in samples grown with different deposition conditions. The results show that the anisotropy is minimized if the deposition pressure is low, the substrate temperature during growth is higher rather than lower, and the substrate is rotated at higher speed, rather than lower, during growth. The quality of the hysteresis in the samples is maximized if they are deposited in an in situ magnetic field that reinforces the natural easy axis of the deposition.
Útdráttur

Í eftifarandi ritgerð eru niðurstöður úr tveimur óháðum rannsóknum birtar. Fyrri rannsóknin snýr að sérstæðum Hall hrifum í Fe$_x$Pt$_{1-x}$ þunnfilmum. Riðstraum er keyrt í gegnum sýnin og sérstæða Hall spennan mæld. Þetta er gert fyrir riðstraum af mismunandi tíðnum. Það kom í ljós að sérstæða Hall spennan sveiflar á sömu tíðni og straumurinn í hverri mælingu. Afl merkisins er fasti upp að 123.7 kHz tíðni, en þar fyrir ofan byrjar aflid að falla með hækkandi tíðni. Ástæðan fyrir þessu falli er talin koma frá takmarkandi þáttum hónun sínisins frekar en takmörkunum í sérstæðu Hall hrifunum sjálftum. Seinni rannsóknin snýr að segulmagnaðri anísótrópiu. í Ni$_{81}$Fe$_{19}$ þunnfilmum. Anísótrópiustuðull er mældur í mismunandi þykkum filum. Út frá þeim gögnum er metið að framlag yfirbörðins til anísótrópiunnar er $K_s = (8 \pm 2) \times 10^{-4}$ erg/cm$^2$. Einmig má sjá að hægt er að hugsa um filmur þykkari en 100 nm sem bulk með anísótrópiustuðul $K_u = 1440 \pm 120$ erg/cm$^3$. Anísótrópiustuðull NiFe filma var einmig mældur í filmum sem voru ræktadar við mismunandi aðstæður. Það kom í ljós að lágmarks anísótrópiustuðull fæst ef þróningar í ræktun er lágur, hitastig undirlagsins er hærra frekar en lægra á meðan ræktun stendur, og snúningshraði undirlagsins er hærri frekar en lægri á meðan ræktun stendur. Bestu gæði hysteresulykkja fékkst ef filmurnar voru ræktadar í ytra sviði sem styrkir nát-túrulegu stefnu auðvelda (e. easy) ássins.
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Abbreviations

e - electron charge
\rightarrow F - Lorentz force
\vec{E}, \vec{E} - Electric field
\vec{v} - Velocity
\vec{B} - Magnetic field
e_i - unit vector along axis denoted by i
I - Electrical current
V_H - Hall voltage
R_H - Hall coefficient
\rho - Resistivity
R_{AHE} - Anomalous Hall coefficient
\rho_{Hs} - Anomalous Hall resistivity
H - Magnetic field strength
H_k - Anisotropy field strength
K_u - Anisotropy constant
M, m - Magnetization
M_s - Saturation magnetization
H_c - Coercivity
MOKE - Magneto-optic Kerr effect
\varepsilon - Dielectric tensor
D - Displacement field
Q - Voigt constant
\mu_0 - Vacuum permeability
N - Number of windings in a solenoid
a - Solenoid radius
\left(\frac{dB}{dT}\right)_{HH} - Helmholtz coil magnetic field calibration
R_{HH} - Helmholtz coil electrical resistance
K_s - Surface anisotropy constant
K_u^B - Anisotropy constant in bulk medium
d - Film thickness
T_{dep} - Substrate temperature during deposition
p_{dep} - Pressure in deposition chamber
P_{dep} - Power used to initiate and maintain plasma for deposition
v_{rot} - Rotation speed of substrate during deposition
Ni - Nickel
Fe - Iron
Pt - Platinum
Py - Permalloy
Au - Gold
Acknowledgments

First and foremost I would like to thank my thesis advisor Prof. Snorri Þorgeir Ingvarsson for his support during my work on this thesis. I would like to thank him for his guidance and encouragement in critical thinking to solve the problems encountered in the research.

Furthermore I would like to thank the members of my research group. Especially Movaffaq Kateb for his help growing samples, measuring characteristics with XRR and optimizing the MOKE setup.

I would also like to thank my collaborators. Asaf Grosz of Ben-Gurion University of the Negev in Israel for the research opportunity he and his group provided. Prof. Gang Xiao of Brown University and Micro Magnetics Inc. for providing the Fe-Pt samples and the research opportunity they provided.

Many thanks go to Tryggvi Kr. Tryggvason and Einar Baldur Þorsteinsson for their assistance with XRR measurements.

Finally I would like to thank my family for their support during my studies.
1. Introduction

The Hall effect has through the ages been used in numerous applications. It is used in Hall probes which are used in modern magnetometers, it is also used in rotating speed sensors which are used for example in the automotive industry. It is even used in the Hall effect thrusters which are low power thrusters used to propel some spacecraft once they have reached space and escaped the gravitational pull of the earth. With the introduction of the anomalous Hall effect it becomes possible to improve existing applications and possibly make new ones [2, 18]. For example by choosing the correct materials it is possible to make more sensitive magnetic field sensors and new magnetic memory devices. There are of course many more applications of the anomalous Hall effect, but they will not be discussed further here.

The first part (Chapter 2) of this thesis will be focused on measuring the frequency response of the anomalous Hall effect in Fe-Pt thin films. The study is done in collaboration with Micro Magnetics Inc. and a research group led by Prof. Gang Xiao of Brown University. At first the theory behind the ordinary and anomalous Hall effects are presented. Then the specifications of the samples are introduced, and the setup used for measurements is described. In the end the analysis of the measured data is presented along with a conclusion and some propositions of what the next steps could be to take the research further.

Magnetic anisotropy is a measure of how much energy is needed to align the magnetic moment of a specific medium along a specific direction. Asaf Grosz et al. [7, 15, 20] have developed planar Hall effect sensors which could be used to make a new generation of magnetometers. The sensors’ resolution is inversely proportional to the magnetic medium’s anisotropy constant.

The second part of this thesis (Chapter 3) is the study of the anisotropy of Ni$_{81}$Fe$_{19}$ permalloy films, and is done in collaboration with Asaf Grosz of Ben-Gurion University of the Negev in Israel. At first magnetic anisotropy is introduced and how it can be extracted from hysteresis loops. After that the Magneto-optic Kerr effect is discussed, and a measurement setup using the Kerr effect to measure magnetic hysteresis loops is presented. Next the samples, that were used to study the anisotropy of thin films, and their growth technique is presented. Finally the analysis of the data and what can be concluded from the measurements is discussed.
1. Introduction

In appendix A the Magneto-optic Kerr effect measurement setup is presented in more detail than in chapter 3. The setup was custom made for the anisotropy measurements and the appendix was written as part of an instructional manual intended for the users of the measurement setup. It includes both an introduction of how to take measurements with the setup and also the technical specification of the setup.
2. Hall Effect

The Hall effect is a well known transport phenomena which arises in a current-carrying conductor when a perpendicular magnetic field is applied to it. This effect is different in origin and strength depending on the type of material the conductor is made of, e.g. in ferromagnetic materials the effect is stronger than in other materials and is known as the anomalous (extraordinary) Hall effect.

2.1. Theory

2.1.1. Ordinary Hall Effect

In an electric conductor a current is the movement of charge carriers (electrons and holes). Typically these carriers travel in a straight line between collisions. When a magnetic field is applied perpendicular to the current, the charge carriers experience a force known as the Lorentz force and travel along a curved path instead of a straight one. This results in one side of the conductor gathering a net charge with respect to the other. This charge results in a voltage difference across the conductor. Figure 2.1 shows a diagram of the movement of charge carriers, both negative (electrons) and positive (holes) ones, and how the Hall effect is generated perpendicular to the magnetic field and current directions. This is the general case in semiconductors. Note that if compared to the charge gathering of electrons, the charge for a hole current gathers on the opposite side of the conductor. This means that when electrons are charge carriers the Hall voltage will be opposite in sign when compared to the Hall voltage generated with holes as charge carriers.

Because of the different charges of electrons and holes let $\tilde{e} = \pm|e|$ where $e = 1.6 \cdot 10^{-19}C$ and $\tilde{v}_x = \pm|v_x|$ where $v_x$ is the velocity of the charge carriers. The minus sign denotes electrons and the plus sign holes. The Lorentz force, which acts on the current-carriers in a magnetic field, is described by equation 2.1 [8, 10]

$$\vec{F} = \tilde{e}(\vec{E} + \frac{\vec{v}}{c} \times \vec{B})$$ (2.1)
2. Hall Effect

Figure 2.1: Schematics for the motion of current carriers in an electric conductor sitting in a magnetic field, $B_z$, perpendicular to the current direction, $I_x$. (top panel) The current carriers in this case are negatively charged, i.e. electrons. (bottom panel) The current carriers in this case are positively charged, i.e. holes.

where $\vec{F}$ is the Lorentz force vector, $\vec{E}$ is the electric field vector, $\vec{v}$ is the velocity vector of the charge carriers; $\vec{B} = B_ze_z$ is the magnetic field vector; and $c$ is the speed of light. Solving equation (2.1) for a steady state and assuming the current only flows in the $x$-direction, $\vec{v} = \vec{v}_xe_x$, gives a relationship between the transverse electric field $E_y$ generated across the sample, and the magnetic field $B_z$ applied perpendicular to the sample.

$$\vec{F} = e\vec{v} \times \vec{B} = eE_xe_x + e\left(E_y - \frac{\vec{v}_x}{c}B_z\right)e_y + eE_ze_z = 0$$ (2.2)

Assuming a perfect conductor the only electric field is the one generated due to the magnetic field, i.e. $E_x = E_z = 0$ V/m. That leaves only one part of equation (2.2),
2.1. Theory

or

\[ E_y = \frac{\dot{v}_x}{c} B_z \]  

(2.3)

The current in the conductor can be directly related to the movement of the electrons

\[ I_x = \dot{e} n \dot{v}_x w t \]  

(2.4)

where \( n \) is the concentration of charge carriers that contribute to the current; \( w \) and \( t \) are respectively the width and thickness of the conductor. Using equations (2.3) and (2.4) the Hall voltage, \( V_H \), can be obtained as

\[
V_H = E_y w = \frac{1}{c e n} \frac{I_x B_z}{t} = \begin{cases} 
-\frac{1}{c |e| n} \frac{B_z I_x}{t}, & \text{for holes} \\
\frac{1}{c |e| n} \frac{B_z I_x}{t}, & \text{for electrons.} 
\end{cases}
\]

(2.5)

It turns out that the Hall voltage for electrons is equal in magnitude as the one for holes, but has opposite sign. This does however not affect the Hall coefficient. The Hall coefficient is then defined as

\[ R_H = -\frac{1}{c \cdot e \cdot n} \]  

(2.6)

The Hall voltages written in terms of that coefficient are

\[
V_H = \begin{cases} 
-R_H \frac{B_z I_x}{t}, & \text{for holes} \\
R_H \frac{B_z I_x}{t}, & \text{for electrons.} 
\end{cases}
\]

(2.7)

This is the general case for a semiconductor.

2.1.2. Anomalous Hall Effect

The anomalous Hall effect is similar to that of the ordinary Hall effect. The difference is that it occurs in ferromagnetic conductors [9], and has a different origin. The anomalous Hall effect is not caused by the Lorentz force acting on the current carrying electrons in the metal conductor. It is however caused by breaking of right-left symmetry due to the spin-orbit interaction of the electrons. The general consensus is to formulate the anomalous Hall effect with equation (2.8) [14]

\[ \rho_{xy} = R_H B_z + 4\pi R_{AHE} M_z \]  

(2.8)

where \( R_H \) is the ordinary Hall effect coefficient and \( R_{AHE} \) is the anomalous Hall effect coefficient caused by asymmetric scattering. The slope of this transverse resistivity
2. Hall Effect

is often called the Hall slope. It is believed that $R_{AHE}$ is mainly caused by three different mechanisms, (1) intrinsic mechanism, (2) skew-scattering mechanism and (3) side-jump mechanism. The anomalous resistivity $R_{AHE} M_z$ is written as a sum of contribution from different scattering mechanisms [11]

$$\rho_{AHE} = A \rho_{xx} + B \rho_{xx}^2$$  \hspace{1cm} (2.9)

where $A$ is a coefficient related to the skew-scattering mechanism and $B$ to the intrinsic and side-jump mechanisms.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure2.2.png}
\caption{Diagrams for the different scattering mechanisms that contribute to the anomalous Hall effect.}
\end{figure}

Some experiments have shown that the anomalous resistivity is directly proportional to the n-th power of the longitudinal resistivity, $\rho_{AHE} \propto \rho_{xx}^n$, where $n > 2$, e.g. $n = 3.7$ has been found in heterogeneous films of Co-Ag. This is in direct contradiction to the model displayed above in equation (2.9) and supports the belief
that the origin of the effect is not completely known. It is entirely possible that the anomalous Hall effect has origin in more mechanisms and material specific elements than those mentioned above. It is also of worth to mention that the anomalous Hall effect is stronger than the ordinary Hall effect in some materials, this is highly dependent on material specific components and whether the skew-scattering or the side-jump component of equation (2.9) is dominant. Since the origin of the anomalous Hall effect is not completely known it is also possible that other mechanisms are dominant.

2.2. Samples

Other studies have shown that Pt-based ferromagnetic thin films can generate a dramatically stronger anomalous Hall effect compared to many other materials. In fact a Hall slope as high as $2.26 \mu \Omega \text{cm/KG}$ has been reported at room temperature (300 K) [13]. The samples investigated here are three Fe-Pt blends of different proportions. These samples are all fabricated by Micro Magnetics Inc. and an affiliate research group led by Professor Gang Xiao at the Physics Department of Brown University. Their characteristics are listed in table 2.1

<table>
<thead>
<tr>
<th>Composition</th>
<th>$R_H$ [Ω/KG]</th>
<th>Hall slope [μΩcm/KG]</th>
<th>$\rho$ [Ωcm]</th>
<th>$R$ [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Fe_{35}Pt_{65}$</td>
<td>0.24988</td>
<td>0.750</td>
<td>$1.25 \cdot 10^{-4}$</td>
<td>104.714</td>
</tr>
<tr>
<td>$Fe_{41}Pt_{59}$</td>
<td>0.18620</td>
<td>0.559</td>
<td>$1.33 \cdot 10^{-4}$</td>
<td>122.154</td>
</tr>
<tr>
<td>$Fe_{47}Pt_{53}$</td>
<td>0.14846</td>
<td>0.445</td>
<td>$1.16 \cdot 10^{-4}$</td>
<td>106.990</td>
</tr>
</tbody>
</table>

The geometry of the samples is a butterfly like shape portrayed in figure 2.3. Contacts $a$ and $b$ are meant for current conductance and contacts $c$, $d$, $e$ and $f$ serve the purpose of Hall voltage measurements i.e. the current goes from contact $a$ to contact $b$ or vice versa, and the anomalous Hall voltage is measured between contacts $c$ and $d$ or contacts $e$ and $f$. 

Table 2.1: Characteristic information about the Fe-Pt alloy thin film samples. $R_H$ is the Hall resistance, $\rho$ the resistivity and $R$ the samples longitudinal resistance.
2. Hall Effect

2.3. Measurement Setup

The setup used to measure the anomalous Hall voltage is shown in figure 2.4. It is a fairly simple setup that consists of a function generator, two voltage and two current probes, a microscope, a magnet and an oscilloscope. The sample that is desired to measure is placed under the microscope on top of a permanent magnet magnetized in the z-direction resulting in a magnetic field perpendicular to the current. Four probes are lowered carefully onto four of the contacts, two of them for current (contacts a and b in figure 2.3) and two of them for the anomalous...
Hall voltage (contacts c and d or e and f in figure 2.3). The function generator is connected to the current probes and set to generate a 100 $\mu$A alternating current at specific frequencies. The voltage probes are connected to an oscilloscope where the anomalous Hall signal can be viewed in real time and stored for later analysis.

2.4. Analysis

Before measurements were taken with the samples described in section 2.2 they were checked for quality. Quality wise there are two variables that are considered. Those variables are the condition of the Hall bar on one hand and the condition of the contacts on the other. The quality control was done by means of visual qualification in a sensitive enough microscope. It turned out that all the samples of composition $Fe_{41}Pt_{59}$ were too badly damaged during shipping, and were not usable in measurements. Either the Hall bar itself was damaged or the connections between the Hall bar and the Hall voltage contacts were no longer viable, i.e. the connections between the Hall bar and contacts c,d,e and f on figure 2.3 were not viable. Some of the $Fe_{35}Pt_{65}$ and $Fe_{47}Pt_{53}$ samples were deemed to be of high enough quality.

For each type of sample a series of measurements were taken. The anomalous Hall signal generated across the sample when it is carrying a 100 $\mu$A alternating current of various frequencies is measured. A typical waveform of the anomalous Hall voltage is displayed on figure 2.5. Although figure 2.5 contains a lot of noise it does not matter because it is in fact the power spectral density of this signal that is used to identify dominant frequency components. Let $x(t)$ be the anomalous Hall signal and $X(j\omega)$ be its Fourier transform.

$$x(t) \leftrightarrow X(j\omega)$$ (2.10)

The power spectral density describes the distribution of the frequency components that the signal is composed of and is simply obtained with equation (2.11).

$$S_{xx} = |X(j\omega)|^2$$ (2.11)

For demonstration the power spectral density that corresponds to the data in figure 2.5 is displayed in figure 2.6.
2. Hall Effect

Figure 2.5: A typical waveform of the anomalous Hall voltage observed in the measurement. This particular measurement is taken with a $Fe_{47}Pt_{53}$ sample at a frequency of 1230 Hz.

Figure 2.6: Power spectral density calculated from a anomalous Hall voltage signal obtained with measurements on $Fe_{47}Pt_{53}$ at a frequency of 1230 Hz. (left panel) The entire power spectra. (right panel) Limited power spectra focused around the dominant frequency component.

For each measurement taken the dominant frequency component of the signal is identified from the power spectral density as showed with the red lines on figure 2.6. Figure 2.7 shows the extracted dominant frequencies and their power in each of the measurements, both for the $Fe_{35}Pt_{65}$ and $Fe_{47}Pt_{53}$ series. The figure also shows the frequency of the current for each measurement, although the power of those data points is arbitrary.
Two things can be concluded from figure 2.7. Firstly, looking at the frequencies extracted from the anomalous Hall measurements and comparing them to the known frequencies used for the alternating current, it is evident that there is a matching between the two signals, i.e. the anomalous Hall voltage is switching direction at the same frequency as the current. This behavior is expected. Secondly, the power of the dominant frequency components is a constant for low frequencies. When the frequency rises above a certain value the power of the dominant frequencies starts to drop. This can be seen from the fact that at 123.7 kHz the power is approximately the same as that for lower frequencies. At 1.237 MHz and above the power is significantly lower. Therefore at some point between 123.7 kHz and 1.237 MHz the power starts to decrease with rising frequency. This behavior was also expected, although the frequency where this would start was unknown. The decrease in power is not believed to be caused by limitations in the anomalous Hall effect. It is rather believed to be caused by a limiting factor in the design of the sample and experimental setup. The samples are not designed with high frequency operation in mind and when the frequency rises it is believed that reflections from the lack of impedance matching is the cause of the fall in power. Other factors causing the power drop could be the change in current conductor symmetry, i.e. the change from the coaxial symmetry of the coax-cable to the geometry of the probes, and from the probes to the in-plane symmetry of the sample. It would
2. Hall Effect

be interesting to get the samples redesigned for high frequency operation, e.g. by changing the contacts from fields to a ground-signal-ground configuration. High frequency samples could be used to test the hypothesis that the anomalous Hall effect is not limiting at frequencies above \( 123.7 \text{ kHz} \). The samples could also be used for an analogous study over an extended range of frequencies, possibly all the way up to the GHz range and even higher if possible.

2.5. Next Steps

There is a clear opportunity to take the anomalous Hall effect study presented in this thesis further. This depends highly on whether or not a sample redesign and fabrication is approved. Suggestion for such a redesign could be to change the contacts to the Hall bars from the direct current geometry of figure 2.3 to a symmetric, impedance matched ground-signal-ground configuration, similar to that of a coplanar waveguide. This is only a suggestion and not in any way an assurance that such a redesign would be possible. With high frequency samples the study presented above could be taken to new lengths. There are known studies that measured the Hall effect operating up to the GHz regime, so it stand to reason that with new samples higher frequency driving current could be used and a study could be made to investigate the frequency properties of those samples for a much wider bandwidth. At least it could be confirmed whether or not the hypothesis presented above is true, i.e. that the limiting factors are the samples and setup and then the physical response of the anomalous Hall effect is not so slow.

This study could also be expanded to include an analogous study where an alternating magnetic field is applied perpendicular to the anomalous Hall bars and a direct current is used to drive them. A study like that presents a whole other set of problems. A device would have to be fabricated that is able to support high frequency magnetic field strong enough to induce an anomalous Hall voltage that can be measured. The magnetic field would also need to be uniform over a large enough area such that is engulfs the sample. Some ideas of how to implement this would be the use of waveguides or antennas. A coplanar waveguide produces a magnetic field between its ground and signal planes. A horn antenna fed with a rectangular waveguide is another possibility. This would have to be studied further, both how strong fields these devices can support, whether they extend over a large enough area and if such devices are feasible to use in the measurement setup. Originally this study was intended to be a part of this thesis, but it was decided to wait due to the lack of proper samples. Typically waveguides operate in the RF (radio frequency) or microwave spectrum. Those frequency ranges contain much higher frequencies than our samples support.
2.6. Conclusion

The Anomalous Hall voltages in Hall bars of two different Fe-Pt composition were studied. An alternating current was passed through the samples and at the same time a magnetic field was applied perpendicular the samples surface, i.e. the direction of the current. After analyzing the power spectral density, of the measured data, it is concluded that the frequency of the anomalous Hall voltage matches the frequency of the current driven through the samples. For frequencies below 123.7 kHz the power in the anomalous Hall voltage is approximately a constant. At a frequency, somewhere between 123.7 kHz and 1.237 MHz, the power of the anomalous Hall signal starts to decrease with rising frequency. This is not believed to be caused by the anomalous Hall effect, but rather the fact that the samples used in the measurements are not designed to receive, and output, high frequency signals. It is believed that with the right samples the frequency matching between the anomalous Hall voltage and the current will continue, and its power will be constant over a much greater bandwidth. This should be the subject of another study, given that a sample redesign is authorized. If this hypothesis is correct the samples tested are a viable possibility for magnetic field sensors. Another interesting study could be made with high frequency samples. That study is the frequency characteristics of the anomalous Hall effect with respect to the applied magnetic field. Is there is matching between the frequency of the anomalous Hall voltage and the frequency of the magnetic field? For such a study the samples should be driven with a direct current.
3. Magnetic Anisotropy

The definition of anisotropy is the property of being directionally dependent. This is the direct opposition of isotropy, which implies directionally independent properties, i.e. identical properties in all directions. Anisotropy can be observed in many different physical and mechanical properties of materials. An example of anisotropy is optical anisotropy where crystals are anisotropic in response to light. The subject investigated in this part of the thesis is magnetic anisotropy of permalloy (NiFe). Magnetic anisotropy is the directional dependence of a material’s magnetic properties. Furthermore a material can have different kinds of anisotropy depending on how the energy surface looks like. In our case we have uniaxial magnetic anisotropy. By adding the distinction of uniaxial it is being stated that the magnetization within the material has one easy axis and one hard axis. The easy axis is the direction in which it takes a minimum amount of energy to magnetize the material, and the hard axis is the exact opposite, i.e. it is the direction where it takes a maximum amount of energy to align the magnetization[3]. The easy axis and the hard axis are perpendicular to each other. The uniaxial energy density is on the form [14]

\[ u_a = K^0_u + K^1_u \sin^2 \theta + K^2_u \sin^4 \theta + \ldots \]  

Equation (3.1) is dependent on \( \sin^n \theta \). With \( \theta = 0, \pi \) a minimum occurs in \( u_a \), i.e. the easy axis, while \( \theta = \frac{\pi}{2}, \frac{3\pi}{2} \) gives the energy maximum of the hard axis. For magnetization along the hard axis the Zeeman energy, \( -\mu_0 M_s H \sin \theta \), is added to the energy density of equation (3.1). Applying the zero-torque condition, \( -\frac{\partial u}{\partial \theta} = 0 \), yields

\[ \mu_0 H M_s = 2K^1_u \sin \theta + 4K^2_u \sin^3(\theta) \]  

Let \( \sin \theta = \frac{M}{M_s} \) so that at saturation \( \sin \theta = 1 \). With \( K^2_u = 0 \) the magnetization saturates at a value of

\[ H_k = \frac{2K^2_u}{M_s} \]  

When measuring the anisotropy of a magnetic materials, hysteresis loops are of great value. A hysteresis loop is a measurement of the magnetization within the sample, \( M \), versus the magnetic field strength, \( H \), or flux density, \( B \), applied across it. Figure 3.1 shows an ideal hysteresis curve for both a easy axis measurement and a hard axis measurement. Easy axis measurement means measuring the magnetization in the sample when the magnetic field is applied in the direction of the easy axis, and the
3. Magnetic Anisotropy

Figure 3.1: Ideal hysteresis loop. (left panel) Along easy axis. (right panel) Along hard axis.

Hard axis measurement when it is applied in the direction of the hard axis. The point on figure 3.1 where the hard axis curve reaches saturation is called the anisotropic field strength $H_k$ and is an indirect measure of the energy needed to align the magnetization of a sample along the direction of the hard axis. $H_k$ can be related to the saturation magnetization $M_s$ and anisotropy constant $K_u$ with equation (3.3). The width of the easy axis curve gives a measure of what field strength is needed to demagnetize the sample in question. This is called the magnetic coercivity, $H_c$, and is equal to half the width of the opening in the easy axis curve.

3.1. Magneto-Optic Kerr Effect

3.1.1. Theory

The magneto-optic Kerr effect (MOKE), discovered in 1877 by John Kerr, describes a rotation of the polarization plane of a linearly polarized light being reflected from an opaque magnetic medium while in an applied magnetic field. It is related to the Faraday effect, discovered by Michael Faraday in 1845. The Faraday effect describes the rotation of the incident light polarization plane in transparent media, i.e. media where the light is not reflected from it but is transmitted through it.

The origin of the magneto-optic Kerr effect can be described in two ways. Either by macroscopic dielectric theory or microscopic quantum theory. According to microscopic quantum theory the effect arises due to the spin-orbit interaction between the
3.2. Measurement System

If a magnetic sample has a uniaxial magnetic anisotropy, said anisotropy can be extracted from a hysteresis curve taken along the hard axis of magnetization. A hysteresis curve is a measurement of magnetization versus applied magnetic field. Since the Kerr rotation is directly proportional to the magnetization it is possible to make a measurement system that uses the Kerr rotation to obtain a hysteresis loop [6, 12, 22]. Such a system measures the Kerr rotation at various strengths in magnetic field and plots the results against each other, i.e. plots the Kerr signal versus the magnetic field strength. Although this doesn’t directly give a measurement that can be scaled to give the correct magnetization in the sample at each field strength, it is possible to calibrate for each sample to give the correct magnetization. This is not necessary to extract the anisotropic field strength or the anisotropy constant. With an independent measurement of the saturation magnetization the anisotropy

electric field of the incident light and the electron spin within a magnetic medium. Since the magnetization of a medium, and by extension the applied magnetic field, directly affects the electron spin it can be concluded that the coupling between the electric field of the light and the magnetization of the medium produce the effect. Macroscopically the magneto-optic Kerr effect arises from the antisymmetric, off-diagonal elements in the dielectric tensor [1, 19]}

\[
\epsilon = \epsilon \begin{bmatrix}
1 & -iQm_z & iQm_y \\
-iQm_z & 1 & -iQm_x \\
iQm_y & iQm_x & 1
\end{bmatrix}
\] (3.4)

The Faraday and Kerr effects can be obtained in the same equation which depends on the dielectric tensor.

\[
D = \epsilon E = \epsilon \begin{bmatrix}
1 & -iQm_z & iQm_y \\
iQm_z & 1 & -iQm_x \\
iQm_y & iQm_x & 1
\end{bmatrix} E = \epsilon E + i\epsilon Q \mathbf{m} \times E
\] (3.5)

where \(D\) is the displacement field vector of the reflected (Kerr) or transmitted (Faraday) beam; \(\epsilon\) is the dielectric tensor; \(E\) is the electric field vector of the incident light; \(Q\) is a material dependent constant called the Voigt constant (often \(\sim M_s\)); and \(\mathbf{m} = [m_x \ m_y \ m_z]\) is the magnetization vector of the magnetic medium. The second part of equation (3.5) corresponds to the magneto-optic effect, Faraday in transparent medium (light transmitted through the material) and Kerr in opaque medium (light reflected from the material). It can now be clearly seen that the macroscopic formalism for the effect gives a direct relation to the electric field of the incident light and the magnetization of the medium.
3. Magnetic Anisotropy

constant can be calculated with equation (3.3). The saturation magnetization can be measured in various ways, including vibrating sample magnetometer (VSM) and superconducting quantum interference device (SQUID) magnetometer.

The system that was constructed for the hysteresis measurements consists of an optical setup that directs a laser beam onto a sample that sits in a magnetic field. Before hitting the sample the beam is passed through a polarizer that ensures the beam is s-polarized. This way, if the coordinate system is defined as being on the surface of the sample, the polarization will be in the plane of the sample and not at an angle to it. This maximizes the signal from the Kerr rotation, as can be seen by the cross product from equation (3.5). Figure 3.2 shows that when the beam is s-polarized the electric field of the light will be in plane with the surface of the sample. This makes the electric field perpendicular to the magnetization, and thereby maximizes the Kerr rotation. However if the beam is p-polarized a smaller a part of the electric field contributes to the rotation and thus the rotation will not be as strong as for the s-polarization.

![Figure 3.2: The coordinate system of the MOKE setup focused around the sample for: (left panel)s-polarized light, and thus E_y and m_x are perpendicular. (right panel)p-polarized light and thus E_y and m_x not perpendicular.](image)

The beam reflected from the sample is passed through another polarizer called an analyzer. The analyzer is set to be approximately perpendicular in polarization direction with regards to the first one. The reason for that is if two polarizers are perpendicular to each other no light will pass through the second one. By using this logic in the MOKE measurement system, the majority of the measured beam is the part that was rotated in the sample while the majority of the original beam is filtered out. After this filtering the intensity of the beam is measured with a photosensitive diode. Technically this is all that is needed for a working MOKE measurement system. However the performance of the system with regards to noise can be improved. In order to do that a chopper was added between the sample and the analyzer and a lock-in amplifier used to measure the signal from the diode on the same frequency as the chopper. This improves the signal to noise ratio in several ways, e.g. with regards to ambient light.
3.2. Measurement System

3.2.1. Equipment

Electromagnet

A key part of successful MOKE measurements is the magnetic field that is applied across the sample, and by extension the magnet that is used to generate that field. The requirements the magnet needs to fulfill, is to support a uniform magnetic field that can be generated in two opposite directions. The maximum strength of said field is of course important, but it is hard to make a magnet that would meet the criteria for all the samples of the world, so it was decided that the magnet should be capable of generating a field of a few tens of Gauss without excessive heating (above 20 W power). Also it was decided that a square sample with a side length of 2 cm should fit in the magnetic field for measurements, therefore the uniformity of the field should be at minimum over a 2 cm × 2 cm area.

After careful consideration it was decided to use an electromagnet called Helmholtz coils [16]. For this setup the Helmholtz coils were custom made to fulfill the requirements above. Helmholtz coils are two identical solenoids of radius \(a\) with \(N\) windings each. The solenoids are placed symmetrically along a common axis with separation equal to their radius. The magnetic field generated between the two solenoids is largely uniform in nature and it’s direction, along the common axis, is dependent on the direction of the current used to drive the coils. The magnetic field on this
3. Magnetic Anisotropy

axis is described by

\[ B = \frac{\mu_0 NI a^2}{2} \left[ \frac{1}{(a^2 + (x + \frac{a}{2})^2)^{3/2}} + \frac{1}{(a^2 + (x - \frac{a}{2})^2)^{3/2}} \right] \]  \hspace{1cm} (3.6)

where \( x \) is the distance from the center between the two solenoids along the common axis, \( I \) is the current, \( N \) the number of windings on each coil, \( a \) the radius of the coils, and \( \mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2 \) is the vacuum permeability.

The specification chosen for the MOKE system is a solenoid of radius \( a = 5 \text{ cm} \) with \( N = 100 \) windings each. Figure 3.4 shows a calibration of the Helmholtz coils, i.e. the magnetic field generated in the coils versus the current driving them. The slope of the best linear fit that goes through the origin gives a characteristic field strength of the coils as

\[ \left( \frac{dB}{dI} \right)_{\text{HH}} = 17.24 \text{ [G/A]} \]  \hspace{1cm} (3.7)

If compared to the theoretical value calculated with equation (3.6) (18 G/A) there is a slight difference. This difference can be explained by the fact that the actual coils are made of 10 layers of windings, each layer consisting of 10 windings. This makes the actual solenoid about 1 cm thick. The derivation of equation (3.6) does not account for this thickness.

![Figure 3.4: Calibration of the Helmholtz coils with regards to current and magnetic field strength.](image)

According to Ohm’s law, the resistance of the coils is obtained by measuring an I-V curve and calculating the slope of the best linear fit that passes through the origin.
Figure 3.5 displays the I-V curve measured. The resistance is calculated from the data as

\[ R_{\text{HH}} = 2.4\Omega \]  

(3.8)

\[ \begin{array}{ccccccccc}
0 & 0.5 & 1 & 1.5 & 2 & 2.5 & 3 \\
\hline
0 & & & & & & \\
1 & & & & & & \\
2 & & & & & & \\
3 & & & & & & \\
4 & & & & & & \\
5 & & & & & & \\
6 & & & & & & \\
7 & & & & & & \\
8 & & & & & & \\
\end{array} \]

\[ I \text{ [A]} \]

\[ V \text{ [V]} \]

\[ \begin{array}{ccccccccc}
0 & 0.5 & 1 & 1.5 & 2 & 2.5 & 3 \\
\hline
0 & & & & & & \\
1 & & & & & & \\
2 & & & & & & \\
3 & & & & & & \\
4 & & & & & & \\
5 & & & & & & \\
6 & & & & & & \\
7 & & & & & & \\
8 & & & & & & \\
\end{array} \]

\[ \text{Measurement} \]

\[ \text{Best linear fit through origin} \]

\[ V \text{ [V]} \]

\[ I \text{ [A]} \]

Figure 3.5: Calibration of the Helmholtz coils with regards to current and voltage, i.e. resistance.

Power Supply

A power supply is needed to drive the electromagnet. In order to get a good range of magnetic field strength from the magnet the power supply needs to support a good range of current. It also needs to be bipolar in order to induce a magnetic field in both directions. Since there wasn’t a bipolar power supply available to the system a unipolar one was used. In addition a relay setup was constructed to act as a polarity changer when negative current was desired. To power the relay a power supply/amplifier, controlled by the computer interface, is used. It switches the relays when the current should be in the negative direction and switches them off again when the current crosses into the positive direction.
3. Magnetic Anisotropy

**Lock-In Amplifier**

The purpose of the lock-in amplifier is to measure a small bandwidth of a signal around a specific frequency. By chopping the light it is turned into a square wave. Using the intensity of that square wave as an input and setting the lock-in amplifier to measure at the frequency of the chopper, a better signal to noise ratio will be obtained compared to measurements without the lock-in. This is because the only part of the signal that is used is the one that is chopped, most ambient light and other noise sources that effect the diode sensor are suppressed.

**Computer Interface**

To control all the parts of the system a computer program was written with the system design software Labview. The interface handles configuration of the lock-in amplifier via a GPIB connection, switches the polarity of the current via a data acquisition (DAQ) board and controls the power supply for the electro magnet via the same device. The DAQ device also handles all measurements that are received from the lock-in amplifier. A GPIB connection was not used for all data handling because of the limited interaction speed it supports.

Appendix A goes into deeper technical details of the setup. It was written as part of an instruction manual for the MOKE setup.

**3.3. Samples**

Discovered in 1914 by Gustav Elmen of Bell Telephone Laboratories, permalloy is a nickel (Ni) - iron (Fe) magnetic alloy. Typically it has about 80% Ni and 20% Fe content and would be called permalloy 80, the number denoting the percentage of Ni in the blend. Because of its very high magnetic permeability, permalloy is useful in applications as a magnetic core material and as magnetic shielding material. Other magnetic properties of permalloy are low coercivity, near zero magnetostriction and significant anisotropic magnetoresistance [4, 14]. Even though, strictly speaking, permalloy does not have a uniaxial anisotropy, it is close enough that the approximation of uniaxial anisotropy is fairly accurate. This enables the use of hysteresis loop measurements to extract the anisotropy.

The study presented in this part of the thesis is focused around the anisotropy of Ni$_{81}$Fe$_{19}$ permalloy films. Figure 3.6 is an illustration of such a film. The thickness dependence of the anisotropy will be studied, along with which sample characteristics
or deposition parameters will minimize the anisotropy constant. All the samples are squares with a side length of 2 cm grown with magnetron sputtering. The NiFe films are grown on top of a Si substrate with a 100 nm SiO₂ layer. By changing the growth parameters such as temperature, pressure, power and deposition time, samples of different thickness, roughness and density are produced. In order to estimate the characteristics of the films a technique known as XRR (X-Ray Reflectivity) is used [23]. From the data acquired with the XRR three parameters can be estimated. Those parameters are the film thickness, the film roughness and the film density. In the case of this study the film thickness was the most reliable parameter extracted, while the roughness and density had a higher error estimate.

3.3.1. Sputtering

Sputtering is a physical vapor deposition technique where atoms are lodged from a target surface by ion bombardment and then carried and deposited to a growth surface (substrate) by an inert gas, typically argon. This is done in a vacuum chamber under various pressures and temperatures. The power, used to create and maintain the plasma that is used to dislodge and carry atoms from target to substrate, can also be varied. All of these parameters along with the growth time have effects on the film characteristics, such as thickness, roughness and density. A clean vacuum chamber and a clean substrate and sample holders are of the utmost importance to get a reliable growth. For this reason the substrates used for deposition are cleaned in an ultrasonic bath using the following process:

1. Substrate cleaned for 10 min. in acetone.

2. Substrate cleaned with methanol for 10 min..

3. Substrate rinsed with Di water.

4. Substrate dried with nitrogen.
3. Magnetic Anisotropy

3.4. Analysis

A few different but highly related studies were performed on the anisotropy and coercivity of Ni$_{81}$Fe$_{19}$ permalloy films. In order to evaluate both the anisotropy and coercivity of the permalloy films the MOKE measurement setup, described in chapter 3.1 and appendix A, was used to measure a hysteresis loop along both the easy and hard axis of magnetization. According to figure 3.1 the coercivity $H_c$ can be extracted from how wide the opening of the easy axis loop is, and from the hard axis loop the anisotropy field, $H_k$, can be determined by evaluating where the magnetization reaches saturation. Figure 3.7 shows typical loops obtained by the MOKE setup. Note that on figure 3.7 the hard axis does not cross through the origin of the coordinate system as it should. This is not caused by the Kerr effect, but is believed to be an artifact from the measurement system. When the anisotropy is being evaluated in such a loop this offset is removed before the saturation field value is determined. Similarly the easy axis can also display an offset from the origin, i.e. not symmetrical around $\mu_0H = 0$ G. This does not affect the evaluation of the coercivity since the opening of the loop is used to evaluate that parameter, not the exact value of where it transition between positive and negative saturation.

The thickness dependence of the anisotropy in permalloy films was studied. All the films grown were of composition Ni$_{81}$Fe$_{19}$. They were grown by magnetron sputtering at room temperature with a power of 150 W, the pressure during deposition was $1.30 \times 10^{-3}$ mbar and the rotation speed of the substrate was 12.8 rpm. The anisotropy and coercivity of those films were extracted from hysteresis loops acquired with the MOKE setup. Figure 3.8 shows the thickness dependence of both the anisotropy field strength and coercivity of Py in the range from 10 nm up to about 260 nm. The data shows that the coercivity of the Ni$_{81}$Fe$_{19}$ films varies only
3.4. Analysis

slightly over the 250 nm range in thickness. This is however not the case for the anisotropy field. The figure indicates that between 10 nm and 50 nm film thicknesses the anisotropy field decreases approximately as \(d^{-1}\), while above 50 nm thickness the anisotropy field remains approximately a constant. If the saturation magnetization is taken as \(M_s = 836 \text{ emu/cm}^3 \) [5] and to be independent of thickness [17], the anisotropy constant for bulk films is approximately \(K_u = 1440 \pm 120 \text{ erg/cm}^3\).

The figure also shows that the 75 nm film is an outlier, i.e. it deviates from the behavior of the other films. Therefore that data point is not used in the evaluation of the data.

By using equation (3.3) along with a saturation magnetization for permalloy, \(M_s = 836 \text{ emu/cm}^3\), the anisotropy constant can be calculated from the data of anisotropic field strength. At low film thicknesses the surface of the films will have more of an impact on the anisotropy compared to thicker films that will be considered as bulk. The anisotropy constant in these thinner films can be related to the ratio of the film volume to it’s area, i.e. the film thickness. This relation is presented in equation (3.9).

\[
K_u = K_u^B + \frac{K_s}{d}
\]

where \(K_u\) is the anisotropy constant; \(K_u^B\) is the anisotropy constant in bulk media; \(K_s\) is the surface contribution to the anisotropy constant; and \(d\) is the film thickness. Using this relation and plotting \(K_u \cdot d\) against \(d\), i.e \(K_u d = K_u^B d + K_s\), the surface contribution to the anisotropy can be extracted by a simple intercept with the y-
3. Magnetic Anisotropy

axis. Figure 3.9 shows this relation. Since the surface contribution is significant at smaller film thicknesses it was decided only to use thicknesses in the range of 10 nm - 50 nm. Above 100 nm the surface contribution is dwarfed by the bulk state. This is better illustrated in figure 3.10 where the anisotropy constant is plotted versus \(d^{-1}\). The last five data points (10 nm - 50 nm thicknesses) fit reasonably well with the \(d^{-1}\) behavior, i.e. the surface contribution is significant. The 75 nm point fits nowhere in the curve which confirms our previous postulation of it being an out-lier. For 100 nm - 260 nm thickness the anisotropy constant is no longer changing, i.e. those films have reached the bulk state. The surface contribution of the anisotropy constant is evaluated as the y-axis intercept of the fitted line in figure 3.9 left, and is \(K_s = (8 \pm 2) \times 10^{-4} \text{ erg/cm}^2\).

During deposition there are a number of tunable parameters that affect the characteristic properties of the films. The parameters are: deposition temperature \(T_{\text{dep}}\), the pressure in the deposition chamber \(p_{\text{dep}}\), the power used to initiate and maintain the plasma during growth \(P_{\text{dep}}\), and the speed, \(v_{\text{rot}}\), by which the substrate is rotated during deposition. By changing these parameters, films with varying characteristics can be obtained. A series of films were grown where each of these parameters were varied. Their anisotropy and coercivity were extracted from hysteresis loops measured with the MOKE setup. Figures 3.11, 3.12, 3.13 and 3.14 show respectively how the coercivity and anisotropy field strength changes with pressure, temperature, rotation speed, and power. All the samples are grown identically, with a deposition
3.4. Analysis

Figure 3.10: The anisotropy constant, $K_u$, versus the inverse of the film thickness, $d^{-1}$.

pressure of $5.30 \times 10^{-3}$ mbar, a power of 150 W, a rotation speed of 12.8 rpm, a growth temperature of room temperature (300 K), and a parallel in situ magnetic field orientation. In each case one of these parameters is changed according to what is being studied. The samples are, like before, grown on a Si substrate with 100 nm SiO$_2$. 
3. Magnetic Anisotropy

Figure 3.11: Pressure dependence of anisotropy and coercivity in Ni$_{81}$Fe$_{19}$ permalloy films.

Figure 3.11 shows that both the anisotropy field and coercivity increase with increased pressure, i.e. in order to minimize those parameters the pressure in the deposition chamber should be minimized. There is a limit on how far the pressure can be decreased before the plasma in the chamber cannot be initialized for deposition. The lowest pressure tried in this study was $1.30 \times 10^{-3}$ mbar.
3.4. Analysis

From figure 3.12 it can be concluded that the magnetic parameters, i.e. anisotropy field and coercivity, decrease with increasing temperature. Especially so the anisotropy field. This is as expected since at higher temperatures the atoms have longer time, and are therefore more likely, to find the optimal lattice position in the film. The highest deposition temperature tried in this study was 100 °C (373 K).
3. Magnetic Anisotropy

By looking at figure 3.13 it can be seen that the anisotropy field and coercivity decreases with increased rotation speed. Thus to minimize those magnetic parameters the rotation speed should rather be higher than lower. The highest rotation speed tried in this study was 12.8 rpm.

Figure 3.13: Rotation speed dependence of anisotropy and coercivity in Ni$_{81}$Fe$_{19}$ permalloy films.
Figure 3.14 shows that the coercivity decreases with increased power. The highest power used in this study was 300 W, but since the difference between the coercivity in the 150 W and 300 W films is small it was decided that the 150 W power would be used in future depositions. The anisotropy field of these films were to high for MOKE setup to detect them, i.e. they were out of range of the electromagnet. They were grown prior to study of other parameters to minimize the anisotropy.

Another deposition parameter studied is an in situ magnetic field, i.e. a magnetic field applied across the substrate in order to force the anisotropic axes of the sample in a given direction. To induce the magnetic field inside the deposition chamber, a pair of magnets are introduced into the sample holder during deposition. Three different orientations of the magnets were tried. Firstly one with no magnets and hence no in situ magnetic field, secondly one where the magnetic field is perpendicular to the direction of the sputtering gun, and finally one where the magnetic field is initially applied parallel to the direction of the sputtering gun. Figure 3.15 shows a comparison of the magnetic parameters between each of these in situ magnetic field orientations. It indicates that a Ni$_{81}$Fe$_{19}$ film has the lowest anisotropy and coercivity when there is no in situ magnetic field across the substrate during deposition. However when a sample is grown that way the hysteresis loops are not as defined as the ones where the sample is grown with an in situ magnetic field. By *not as defined* two things are being implied. Firstly that the opening of the easy axis is not square, i.e. instead of an instant transition from negative (positive) to positive (negative)
3. Magnetic Anisotropy

In situ magnetic field dependence

![Graph showing Coercivity and Anisotropy field strengths for Ni₈₁Fe₁₉ for different magnetic field orientations.]

Figure 3.15: Coercivity and anisotropy field strengths of Ni₈₁Fe₁₉ for different magnetic fields orientations applied across the substrate during deposition.

Saturation the transition happens in smaller steps which makes the loop more round at the edges. Secondly that the hard axis is possibly not closed in the middle, i.e. the magnetization when going from positive to negative saturation does not return to the same values as when going from negative to positive saturation. Figure 3.16 shows such a hysteresis loop, and if compared to the well defined loops of figure 3.7 the difference is clear in the easy axis loop. The difference of the hard axis is more subtle since the opening in the hysteresis is very small. Even though the films grown with the magnets in the parallel orientation exhibit higher anisotropy and coercivity, the parallel orientation is preferred over the perpendicular and no magnetic field orientations. This is because the hysteresis loops are best defined with the parallel orientation which reinforces the axis orientation of a growth without magnets. The quality of the hysteresis loops is considered to be more important than to get the absolute minimum of the anisotropy.
3.5. Conclusion

When the thickness of a thin-film is below a certain value some of the characteristics in the film deviate from the constant bulk value of thicker films. The parameters that do this become dependent of thickness, often they vary proportional to $\frac{1}{d}$. For the case of magnetic anisotropy this is the fact. The anisotropic constant can be modeled by equation 3.9. If the film is considered to be bulk the $\frac{K_s}{d}$ portion of the equation vanishes and can be omitted, but below a certain film thickness the surface factor will be significant. According to the data on figure 3.9 the surface contribution to the anisotropy constant in Ni$_{81}$Fe$_{19}$ permalloy films is $K_s = (8 \pm 2) \times 10^{-4}$ erg/cm$^2$. For film thicknesses above approximately 100 nm the surface contribution has vanished and the film can be considered bulk. This is further reinforced by the data in figure 3.8 where the anisotropy field settles to a value of $H_k \simeq 3.5 \pm 0.2$ G for thicknesses above approximately 100 nm, with saturation magnetization of $M_s = 836$ emu/cm$^3$.
3. Magnetic Anisotropy

that corresponds to an anisotropy constant of $K_u = 1440 \pm 120 \text{ erg/cm}^3$. This is illustrated on figure 3.17.

![Figure 3.17: Illustration where the surface of the permalloy films is considered significant and where the films are considered to be bulk. (left panel) Thickness dependence of $H_k \cdot d$. (right panel) Thickness dependence of $H_c$ and $H_k$.](image)

All aspects of the deposition of Ni$_{81}$Fe$_{19}$ permalloy films affects the film properties in some way. In this thesis a study has been made to see how the anisotropy and coercivity of permalloy films vary with different deposition parameters. The goal was to identify how to minimize the anisotropy constant. The parameters investigated here were the pressure in the deposition chamber during deposition, the temperature of the substrate during deposition, the speed at which the substrate was rotated during growth, the power used to initiate and maintain the plasma, and whether or not an in situ magnetic field applied across the substrate had any affect. From the data presented above the following can be concluded about each of these parameters:

1. The anisotropy and coercivity of the films increase with increasing pressure. To minimize the anisotropy constant with regards to deposition pressure, the deposition pressure should also be minimized. One has to be careful because if the pressure is decreased to much it can affect the plasma in the deposition.

2. The anisotropy and coercivity decreases with increasing temperature, the anisotropy more so. This means that in order to minimize the anisotropy constant one would want to grow samples at higher temperatures rather than lower.

3. The anisotropy and coercivity decreases with increased substrate rotation speed during deposition. Therefore in order to minimize the anisotropy constant higher rotation speeds are preferred.

4. The films we had with varying power were deposited with totally different
parameters than the other films. The anisotropy field in those films were so high that they were out of range of the MOKE setup.

5. With regard to in situ magnetic field orientation, a growth without in situ field yields the lowest anisotropy, but at the same time the hysteresis loops for those samples are of poor quality. The perpendicular in situ orientation has the next lowest anisotropy, but also has hysteresis loops of poor quality. The parallel in situ orientation reinforces the axis orientation of a growth without magnets. It has the biggest anisotropy, but unlike the other orientations the loops are well defined. This is the reason why the parallel orientation is preferred over the others, even though it does not minimize the anisotropy constant.

In conclusion if the anisotropy of Ni$_{81}$Fe$_{19}$ films grown with magnetron sputtering is to be minimized the following should be applied during sputtering: the pressure should be minimized without it affecting the quality of the plasma; the temperature of the substrate during deposition should be higher rather than lower; if it is possible to rotate the sample it should be done at a higher rotations speed rather than a lower one.

3.6. Further research opportunities

It is well known that permalloy exhibits different magnetic properties if it is grown on top of a Tantalum (Ta) layer [21]. The reason for this is that the Ta provides good wetting properties for a permalloy growth. That means that the permalloy film will be of higher quality. It is also possible to grow a Ta layer on top of the permalloy film. This is not done to get a better film, but is used as a protective layer. It prevents oxidation of the permalloy and thereby ensures that the film does not change over time. An interesting study is to make two different multilayer structures of Ta and permalloy, one with both a Ta under layer and a protective over layer, and the other with only a Ta protective over layer. An illustration of these multilayer structures are shown on figure 3.18. A thickness study of those two multilayer structures is on going and will give an interesting comparison to the thickness and surface contribution study presented in this thesis.
3. Magnetic Anisotropy

<table>
<thead>
<tr>
<th>Ta</th>
<th>Ni$<em>{81}$Fe$</em>{19}$</th>
<th>Si/SiO$_2$(100 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ta</th>
<th>Ni$<em>{81}$Fe$</em>{19}$</th>
<th>Ta</th>
<th>Ni$<em>{81}$Fe$</em>{19}$</th>
<th>Ta</th>
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<td></td>
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</tbody>
</table>

Figure 3.18: Two multilayer structures where Ta is used in conjunction with Ni$_{81}$Fe$_{19}$. (left panel) Ta under layer, (right panel) Ta under layer and a Ta protective layer on top. Both are illustrated as grown on a Si substrate with 100 nm of SiO$_2$. 
Bibliography


A. MOKE instructions

A.1. Introduction

This document is meant as guidelines on how to set up and operate the MOKE measurement setup. It does not provide extensive theoretical background to the physics the setup is built upon. It specifies what equipment is needed and how to connect it together. It also specifies how to operate the corresponding Labview VI that controls the setup and takes measurements.

A.2. The System

A.2.1. The Setup

The setup was constructed in order to detect the MOKE signal, i.e. the rotation of the lasers polarization. It consists of a laser, optical equipment such as polarizing filters and mirrors, an electromagnet, a chopper, a diode and various measurement equipment and power supplies.

- Stanford Research Systems Model SR830 DSP Lock-In Amplifier
- HP 6826A Bipolar Power Supply/Amplifier
- Delta Elektronika Power Supply ES 030-5
- National Instruments Data Acquisition Device (DAQ)
- Thor Labs PDA36A-EC Si Amplified Detector (Diode)
- Two rotatable polarization filters
- Chopper with adjustable frequency
A. MOKE instructions

- Helmholtz coil
- Mirrors
- Laser
- Other equipment needed for the setup such as platforms for the optical part and wires for the signals passed to, from and within the system.

Figure A.1: Diagram showing the interconnectivity and equipment needed in the MOKE setup.

Figure A.1 shows a diagram that illustrates the system that was constructed. The laser sends a beam that is directed towards a sample with a mirror setup. Before the beam hits the sample it goes through a polarizer making the beam vertically polarized with regards to the incidence plane. This makes the electric field of the beam oscillate in the plane of the sample. After the beam goes through the polarizing filter it hits the sample, which is sitting in the middle of Helmholtz coils. The coils are used to generate a uniform magnetic field. It is important that the magnetic field has a direction which is in-plane with the sample surface, not at an angle to it. The field should also be perpendicular to the polarization direction of the incident light beam. As the beam hits the sample the polarization direction is rotated proportional to the samples magnetization and the electric field of the laser.
This relation is displayed in equation (A.1).

\[
D = \varepsilon E + i\varepsilon Q \mathbf{m} \times \mathbf{E}
\]  

(A.1)

where \( D \) is the displacement field vector of the reflected (Kerr) or transmitted (Faraday) beam; \( \varepsilon \) is the dielectric tensor; \( \mathbf{E} \) is the electric field vector of the incident light; \( Q \) is the Voigt constant; and \( \mathbf{m} = \begin{bmatrix} m_x & m_y & m_z \end{bmatrix} \) is the magnetization vector of the magnetic medium.

The complex part of the displacement field corresponds to the Kerr signal. To maximize it, the cross product needs to be maximized. This is done by keeping the electric field s-polarized, i.e. vertical and thereby in the plane of the sample and perpendicular to the magnetization in the sample.

The beam reflected from the sample has a different polarization direction which needs to be detected. To detect that difference the reflected beam is passed through a polarizing filter (analyzer). The analyzer has a polarization direction that is almost perpendicular to the first polarization filter. The reason for that is that if two polarizing filter are perpendicular to each other no light will pass through the second filter. The same applies here. If there is no rotation of the polarization direction there will be a very small amount of light that would go through the analyzer. The bigger the rotation is more light will pass through the analyzer, and thus a bigger signal will be detected. This signal is finally measured with a photosensitive diode.

In order to minimize noise in this setup a chopper is placed between the Helmholtz coils and the analyzer. The chopper serves the purpose of chopping the signal, i.e. transforming the signal into a square wave of a certain frequency. The diode is then connected to the input of a Lock-In amplifier that is set to measure at the same frequency as the chopper (the choppers reference output is connected to the lock-ins reference input). That way only a small bandwidth around the frequency of the wave is being measured, and much noise is being omitted.

Essential to the correct operation of the system is the magnetic field being bipolar. This can be done easily with a bipolar power supply. Since such a power supply was not available, the system uses a regular power supply along with a relay setup. The relays switches the polarity of the coils when activated.

All of this is controlled with a computer through both a GPIB connection to the Lock-In amplifier and a National Instruments DAQ (Data Acquisition) device. The DAQ device is connected to the power supply to control the current on the output terminal, it is also connected to the control input of the relay setup by means of an amplifier. The output of the relays is connected to the Helmholtz coils. For the computer to control the system correctly certain connections need to be in place:

- Pins 63 and 64 on the DAQ device are connected to wires 1 and 5 respectively on the serial input at the back of the Delta Elektronika power supply.
A. **MOKE instructions**

- Pin 31 and 32 on the DAQ are connected to the HI and LO inputs on the HP 6862A.

- Pins 4 and 5 on the DAQ are connected to the Channel 1 Output of the Lock-In Amplifier via a coaxial cable. (Pin 5 is ground).

- The HI output of the HP 6826A is connected to the relay setup control wire that has a capacitor connected to it. The LO output is connected to the other control wire.

- The output of the Delta Elektronika Power Supply is connected to the input of the relay subsystem.

- The output of the relay subsystem is connected to the Helmholtz coils.

- The output of the Thor Labs photosensitive detector is connected to the A/I input of the Lock-In Amplifier.

- The reference signal from the chopper is connected to the REF IN input of the Lock-In Amplifier.

- The DAQ device is connected to the computer via its USB connection.

- The Lock-In Amplifier is connected to the computer via a GPIB connection with GPIB-address number 4.

**A.2.2. The Sample**

When placing a new sample into the setup two things need to be kept in mind. The first one is that the sample needs to be approximately in the middle of the Helmholtz coils in order to get the most uniform magnetic field and for the calibration of the coils to be correct. The other one is that the sample needs to be placed such that the magnetic field is in-plane with the sample. Figures A.2 and A.3 show example schematics of correctly and incorrectly installed samples respectively. The size of the sample is not of extreme importance just as long as it fits between the coils. However it is worth mentioning that the smaller the sample is the more uniform the field is that engulfs it. To fix the sample in between the coils it is attached to the end of a plastic rod with double sided tape. The rod is then fastened to a vertical platform. The platform can be moved along three separate axes in order to get the sample in the desired position. The sample can also be rotated a full 360° about the axis of the rod. When fixing the beam on the sample, the beam should be placed so it is approximately on the middle of that rotation axis. This will give the best
A.2. The System

Figure A.2: Correct sample setup seen from above or from the side. (left panel) Correct sample setup from above. (right panel) Correct sample setup from the side.

Figure A.3: Some examples of incorrect sample setups seen from above and from the side. (top left panel) Incorrect sample setup seen from above. (top right panel) Incorrect sample setup seen from the side. (bottom panel) Incorrect sample setup seen from above.
A. MOKE instructions

measurements across the range of the rotation.

A.2.3. The Computer Interface

When taking measurements with the MOKE setup a computer interface is used. The interface was built with National Instruments system design software Labview. The interface consist of numerous panels, each of which serves a different purpose. For the hysteresis measurements the program steps a DC current through the Helmholtz coils. At each step it reads the signal from the Lock-In Amplifier. One loop in the program is defined as going from a predetermined maximum/minimum value to another predetermined minimum/maximum value and back again. The number of points obtained along the way can be set by changing the step size, but that variable determines how far there is between consecutive readings.

Front Panel

The front panel of the interface is displayed in figure A.4 and is the part that is displayed when the program is first opened. The left hand side of the panel, also displayed on figure A.5 is a section where all of the configurations for the upcoming measurements are made.

Figure A.4: Front panel of the computer interface used to control the MOKE equipment.
A.2. The System

The entire left panel of the configuration interface (figure A.5) is dedicated to the configuration of the lock-in amplifier. The right panel is to adjust the magnetic field values for the upcoming measurements. The possibility to save the measured data is also in the right panel. The Start measurements button starts taking measurements for the hysteresis loops. Before the button is pressed a measurement mode must be set by selecting the appropriate tab and the right half of the panel. There are three kind of measurement modes available: One loop, Continuous and Averaging. The Wait for stability field indicates how long to wait after each time the magnetic field has been changed. This is done to minimize any fluctuation due to the change in field strength. The Calibration field indicates the calibration of the electromagnet. In conjunction with the Maximum, Minimum and Step fields, it computes what current the electromagnet needs at each step. Finally the Starting point field indicates where in the hysteresis loop you want to start.
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One loop:
Figure A.6 shows the interface that measures only one loop.

![Figure A.6: The One loop part of the interface.](image)

When the One loop tab is selected only one hysteresis loop is measured, i.e. when the first loop finishes the measurements stop.

Continuous:
Figure A.7 shows the part of the interface used for continuous measurements.

![Figure A.7: The Continuous part of the interface.](image)

When the Continuous tab is selected the program runs consecutive hysteresis loops, one after another, until the Stop Measurements button is pressed. All the measurement data is stored in a matrix and can be saved to a data file after the measurements are complete. The small graph on the continuous tab shows the most recent hysteresis loop, while the bigger graph shows all of the data obtained.

Averaging:
Figure A.8 shows the part of the interface that continuously takes real time averaging over a predetermined number of loops.

![Figure A.8: The Averaging part of the interface.](image)

When the *Averaging* tab is selected the program runs continuous measurements just like the *Continuous* tab, except it takes the average over a number of hysteresis loops. The small graph shows the average over the last set of loops completed, and the big graph shows the real time average over the current set of loops.

### A.3. Step-By-Step

When first taking measurements with the system the following steps can be a good process to go through to minimize trouble and getting the optimum signal.

1. Before taking measurements the laser should be allowed to settle to eliminate any drift that is possible in the beam itself. This is done by turning on the laser and waiting some time before using it in measurements.

2. Make sure that all the connections and equipment described above are in place and that everything is turned on. Don’t forget to turn on the diode, this is necessary since the Thor Labs diode has a built in amplifier.

3. When the sample has been placed correctly in between the two magnets of the Helmholtz coil, the laser beam should be placed approximately in the middle of the rotation axis of the sample. This minimizes the need to adjust the analyzer and the diode after the sample is rotated.

4. The beam reflected from the sample needs to pass through the chopper, the
A. MOKE instructions

analyzer and the into the diode. To get the best signal possible it is best if
the beam passes straight through them, i.e. is approximately perpendicular to
the analyzer surface. This can be done easily in two steps. Firstly by placing
the reflection from the analyzer on the edge of the chopper opening. Secondly
by ensuring that the beam that passes through the analyzer hits straight onto
the diode. This can be done by having the diode parallel to the analyzer and
having the beam hit straight onto the smallest opening of the diodes iris. This
needs to be done every time the sample is adjusted.

5. Keep all lights turned off and avoid touching any of the equipment during
measurements.

6. When steps 1-4 have been completed and an acceptable signal has been ob-
tained it is time to start taking measurements. Before starting measurements
the AUTO PHASE button should be pressed to minimize the offset in the
signal.

When looking for the hard or easy axis of a sample, and what field strength is needed
to reach saturation, I advice to use a coarse step size and a small time constant on
the lock-in amplifier. For example a step size of 1 or 2 G can be used with a time
constant of 10 or 30 ms. This expedites the process of finding the correct axis and the
saturation field strengths and thereby maximizes the efficiency of the measurements.
When the axis has been located within an acceptable angle the step size should be
lowered to get a finer hysteresis, and the time constant should be increased to 100
ms or above in order to get the most stable signal. This can be described by the
following steps.

1. Set the Step size to a relatively big number, although not to big for the hys-
teresis to be clear.

2. Set the Time constant of the lock-in amplifier to a small number (10 or 20
ms).

3. Measure one hysteresis loop. The One loop function is convenient for this.

4. Rotate sample and repeat step 3 until the hysteresis loop shows the charac-
teristics you are looking for.

5. Set the Step size to the number you wish in your measurements.

6. Set the Time constant of the lock-in amplifier to 100 ms or higher. This
ensures that the signal has settled before reading it from the lock-in output.

7. Start the measurements you wish to take.
8. If using the *Continuous* or *Averaging* functions wait for the program to measure enough loops and then press the *Stop Measurements* button.

9. If you wish to save your data you can choose between using the current date and time as a file name, or making one your self. If you wish to use a filename the button in the save section needs to point to *Use file path* and to use the date it needs to point to *Use date*. For both options the file will be located in the folder specified in the *File path* text box.

### A.3.1. Tip for hard axis determination

When locating the axes of the magnetic anisotropy the absolute hard axis is easier to determine. When a hysteresis shows hard axis behavior one has to have one thing in mind. The hard axis is symmetric around zero magnetic field. If measurements are taken a few degrees away from the true hard axis the hysteresis loop still looks like a hard axis, except it is not symmetric around $\mu_0 H = 0$ G. Figure A.9 shows two hysteresis loops taken a few degrees from the true hard axis. Looking at the figure one can see that when the magnetization approaches saturation the transition is smooth for one of the magnetization direction and more abrupt for the other one. The left figure is smooth for around positive saturation and abrupt around negative saturation. The opposite is true for the right figure. When hysteresis loops like this are measured one should turn the sample by a few degrees at a time until a symmetrical loop is observed. Figure A.10 show such a symmetrical loop, where the transition to positive and negative magnetization is approximately identical.
A. MOKE instructions

Figure A.10: A true hard axis hysteresis loop. The symmetry of transition to positive and negative magnetization is evident.

When such a loop has been obtained it is very simple to find the easy axis. One merely turns the sample a full $90^\circ$ in either direction.
B. CGS to SI conversions

In magnetism there are two unit systems that are used. The centimeter-gram-second (CGS) unit system is commonly used in the United States, while the International System of Units (SI) is commonly used in Europe. The equations and quantities of this thesis are displayed in the CGS unit system. With regards to the SI system some of the equation and most of the magnetic units would need to be converted to apply to that standard.

With regards to the Hall effect (chapter 2), the equation for the Lorentz force (equation (2.1)) would be converted by setting the sound velocity $c$ to unity. The final equation for the Hall voltage (equation (2.7)) would be unchanged while the Hall coefficient of equation (2.6) would change to correspond with the Lorentz force:

$$R_H = -\frac{1}{en}. \quad (B.1)$$

In the anomalous Hall voltage we would see a change from equation (2.8) to:

$$\rho_{xy} = R_H B_x + R_{AHE} M_z. \quad (B.2)$$

With regards to chapter 3 the equations are all displayed in the CGS unit system. The conversion of those equations are done by converting the units of each variable from CGS to SI.

Some important conversion relations connected with this thesis are the conversions of units from CGS to SI. Table B.1 displays the conversion factors when going from SI to CGS or vice versa. When going from CGS to SI units the CGS quantity is multiplied by the conversion factor. The SI quantity is therefore divided by the conversion factor when converting from the SI units to CGS units.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Variable</th>
<th>CGS unit</th>
<th>Conversion factor</th>
<th>SI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic flux density</td>
<td>B</td>
<td>Gauss [G]</td>
<td>$10^{-4}$</td>
<td>Tesla [T]</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>H</td>
<td>Oersted [Oe]</td>
<td>$\frac{10^3}{4\pi}$</td>
<td>A/m</td>
</tr>
<tr>
<td>Magnetization</td>
<td>M</td>
<td>emu/cm$^3$</td>
<td>$10^3$</td>
<td>A/m</td>
</tr>
<tr>
<td>Volume energy density</td>
<td>K</td>
<td>erg/cm$^3$</td>
<td>$10^{-1}$</td>
<td>J/m$^3$</td>
</tr>
</tbody>
</table>

Table B.1: Conversion relations between the CGS unit system and SI unit system. $\text{SI unit} = \text{Conversion factor} \times \text{CGS unit}$