Magnetic Anisotropy

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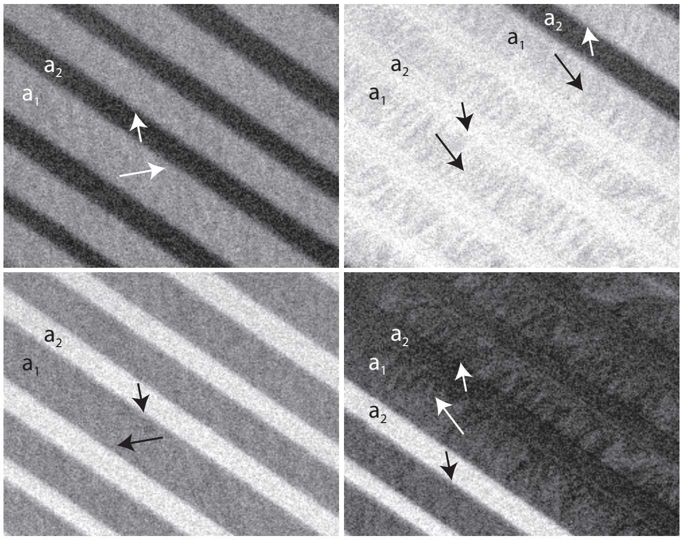

Contents

1 Introduction

The phenomena of magnetism has been known for over three thousand years, and is still widely utilized in industry and intensely studied. Improvements in control and detection of magnetism have provided exponential growth in hard-disk drive storage capacity and even car manufacturers have recently started to install magnetic sensors abundantly (e.g. over twenty magnetic sensors in latest BMW models). One of the main aspects of magnetism is the control of the magnetic anisotropy, where anisotropy means difference in energy depending on the direction of magnetization. For example, it is essential that we know that the magnetization is always pointing either up or down in hard disks drives (HDDS) as these devices store information using the magnetization direction.

The purpose of this experiment is to understand the fundamentals of magnetic anisotropy and learn how to apply general theoretical models to experimental results. The studied sample, a thin magnetic film, is also a fundamental part of more novel structures which have gained immense interest in both industry and scientific research. In those more complex structures,the magnetic anisotropy can be varied during operation using electric fields and currents. However, as those structures are highly resistive (>100 MΩ), the required power ($P = UI$) is nearly zero. Researchers have proposed that these could be used in various devices such as in microwave filters, in magnetic memories and in ultra-low power magnetic computing.

2 Magnetism

2.1 Units in Magnetism

First of all, different units in magnetism are confusing, and their usage varies in different context. Often, there are three fundamental unit: magnetic field $\boldsymbol{H}$, magnetization $\boldsymbol{M}$ and magnetic flux density $\boldsymbol{B}$. $\boldsymbol{H}$ represents the magnetic field, which is similar to $\boldsymbol{E}$ of electric field. The unit of $\boldsymbol{H}$ is A/m, since fundamentally a magnetic field is generated by electric current, where the simplest case is an infinite straight wire. $\boldsymbol{M}$ is the magnetization of the magnetic moments, and describes the response of the material to a magnetic field. $\boldsymbol{M}$ shares the unit with $\boldsymbol{H}$ of A/m since material magnetization can be viewed as a collection of tiny electronic currents with magnetic field $\boldsymbol{H}$. $\boldsymbol{B}$, on the other hand, is the flux density of magnetic field lines per area, with the unit of T or Wb/m^2. It is a useful in describing the effects of the magnetic field on the item occupying a given area. A relation between $\boldsymbol{H}$, $\boldsymbol{M}$ and $\boldsymbol{B}$ can be written as:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}). \tag{1}$$

where μ_0 is the vacuum permeability. As implied by this linear relation, a magnetic material can be described by two quantities and another one can be easily derived. In this lab, we will use $\boldsymbol{H}$ representing magnetic field and $\boldsymbol{M}$ representing material magnetization.

2.2 Different Types of Magnetism

Magnetism is a result of the spin and orbital motion of electrons. The very basic 'magnet' is a single electron spin without orbital moments, and the value of its magnetic moment

is equal to a Bohr magnet $\mu_B = 9.27 \times 10^{-24} Am^2$. The orbital magnetic moment is also quantized in μ_B due to its quantum nature.
In different materials, there are three type of magnetism: Diamagnetism,Paramagnetism and Ferromagnetism.

- Diamagnetic material shows opposite magnetization $\boldsymbol{M}$ according to the applied magnetic field $\boldsymbol{H}$. In diamagnetic materials, the electrons are fully paired, so each tiny magnet of electrons are cancelled out by its opposite pair. As a result, there is no magnetization in electron level. We can then consider the orbits of each paired electrons. Those orbits can be considered as tiny current loops, where, under Lenz's law, when the external field is applied, an opposite direction of the magnetic field is generated.

- Paramagnetic material shows a net magnetization $\boldsymbol{M}$ only when a magnetic field $\boldsymbol{H}$ is applied, and $\boldsymbol{M}$ is in the same direction of $\boldsymbol{H}$. Microscopically, there are some tiny magnets with magnetization by unpaired electrons without the magnetic field applied. Those magnets, however, are thermally disordered at certain temperature. Thus, when a magnetic field is applied, the disordered magnets can be aligned by the external field, showing a net magnetization.

- Ferromagnetic material is able to show a net magnetic moment $\boldsymbol{M}$ without any magnetic field below certain temperature T_c. Instead of disordered tiny magnets, the electrons in ferromagnetic materials are aligned due to the extra energy lining up the adjacent electron spins. This energy is called exchange coupling, which can be calculated using quantum mechanics.

Those three types of magnetism has been arranged in the order of generality: diamagnetism exits in all materials, because all electrons, whether paired or un-paried, form tiny currents when they move around the nuclei. The repulsion according to Lenz's law universally exists, but is rather negligible. Paramagnetism is less general then diamagnetism, due to the fact that unpaired electrons are required. Signal from paramagnetism is commonly larger than diamagnetic signals. In reality, both paramagnetism and diamagnetism show small magnetic signals, so that they are not useful technologically. Furthermore, ferromagnetism required both unpaired electrons and exchange interaction among neighbouring electrons. Noting that the exchange energy can be overwhelmed by thermal disordering, so that above certain temperature, the Curie temperature T_c, ferromagnetism becomes paramagnetism. Many alloys containing Cobalt, Iron and Nickel are ferromagnetic [1, 2].

3 Ferromagnetism

In this lab, we will focus on ferromagnetism. Ferromagnetic materials have a non-linear behavior, which is the building block of many applications.

3.1 Magnetic Hysteresis

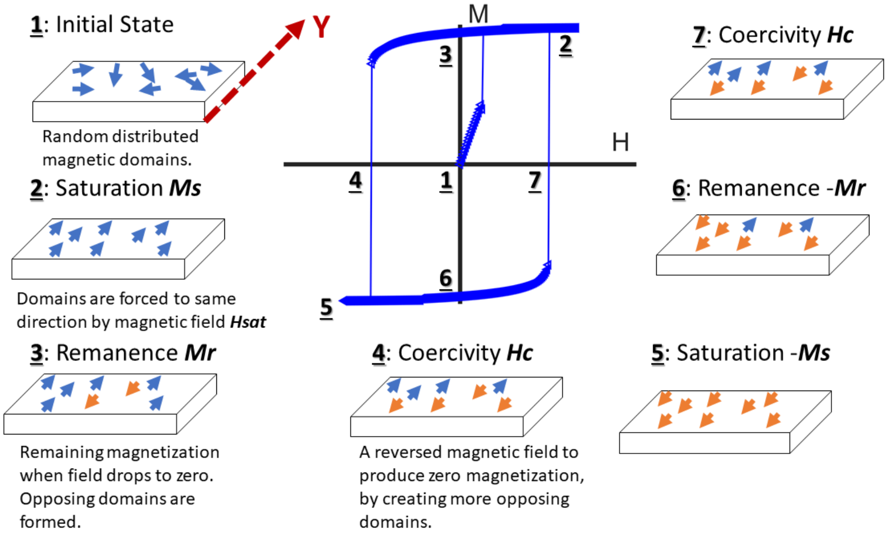

Figure 1: An example of a hysteresis loop of a ferromagnetic sample with the magnetic field sweeping slowly in y-direction (indicated by red dotted arrow), from 0 to $+y$ to $-y$ and back to $+y$. The corresponding $\boldsymbol{M}$ is projected in y direction.

A hysteresis loop is the representation of ferromagnetism. It describes the direction of sample magnetization according to the external magnetic field. The magnetization is projected along a certain axis, typically the direction of the external magnetic field (for example: y-axis):

$$M = \boldsymbol{M} \cos\phi, \tag{2}$$

where $\boldsymbol{M}$ is the normalised magnetization and ϕ is the angle between the magnetization and y-axis. If the magnetization is in xy-plane, it is commonly called 'in-plane'. In this experiment, we will study a sample with uniaxial in-plane anisotropy where at zero field (**3 and 6** in Fig. 1), the magnetization aligns parallel to so-called easy axis. This easy axis is the preferential direction of magnetization.

Fig. 1 illustrates a typical hysteresis loop (M_y-component). The external field is applied along the y-direction. At positive saturation field (H_{sat}) M is (almost) parallel to the external magnetic field in y-direction. When the field is slowly decreasing (moving from positive towards negative fields), the magnetization rotates slowly towards the easy-axis and reaches remanent magnetization at $H = 0$ where M is parallel to the easy axis. The measured remaining M is called remanence M_r. When the field is further increased, M rotates away from the easy axis until there is an abrupt change occurring at the switch field H_{switch} where M_y suddenly drops to zero and jumps over the y-axis. The H_{switch} is also called coercivity H_c. Further increase of the field rotates M parallel to the negative y-axis. If the field is now increased from negative saturation, M follows symmetry upper path and the remanent magnetization has an opposite sign. This non-linear response of the magnetization results in so-called hysteretic behaviour [2] where the system 'remembers' the history of the external magnetic field. There are numerous methods to measure the hysteresis loop of a magnetic sample such as the Hall effect, Superconducting Quantum Interference Device and the magneto-optical Kerr effect. The latter is our method of preference and will be discussed in more detail later.

3.2 Magnetic Domains

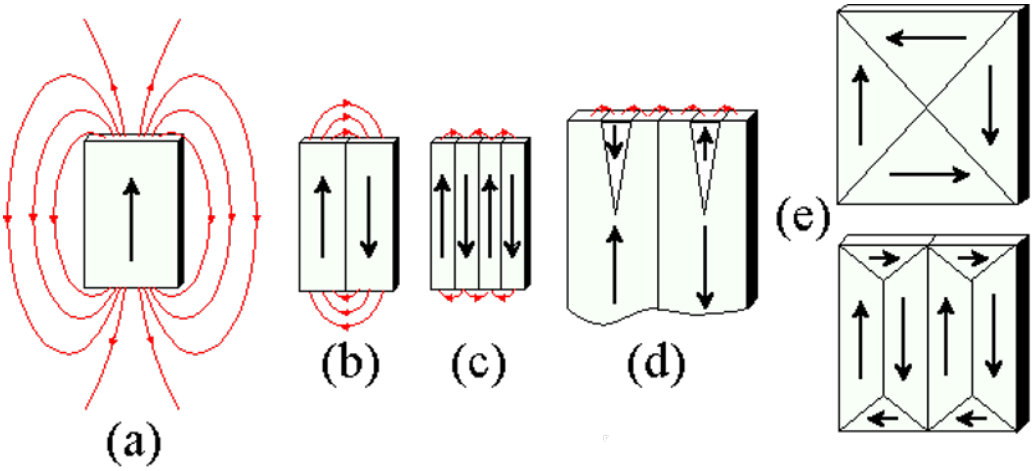

Figure 2: Magnetic stray field from samples with different domain patterns. Generally, the energy of stray field decreases with a increasing amount of domains. Figure from [14]

Magnetic hysteresis is a representation of the average magnetization of a sample. One might be mislead into thinking that a ferromagnetic sample undergoes a switching procedure, where the entire magnetization of the sample coherently rotates. This is not the case for a typical ferromagnetic sample larger than $1\mu m$. To minimize energy from magnetic dipoles of sample surface, magnetic domains (Figure 2) are formed. These are areas where the magnetization is uniform and are typically between $1\mu m$ and $1000\mu m$ in size. Magnetic domains generally come from a competition between two energies: more domains decrease stray field energy, while the exchange energy favors an uniform spin direction.

Go back to Figure 1, where 'magnetization' can be considered as 'magnetic domain', and is represented by arrows with different colors. Thus, the hysteresis loop describes the orientation of magnetic domains. If the magnetic field is large enough, then the domain will oriented to the field direction. Otherwise the domains will tend to arrange along the preferred direction, which lowers the overall energy.

3.3 Single domain behavior

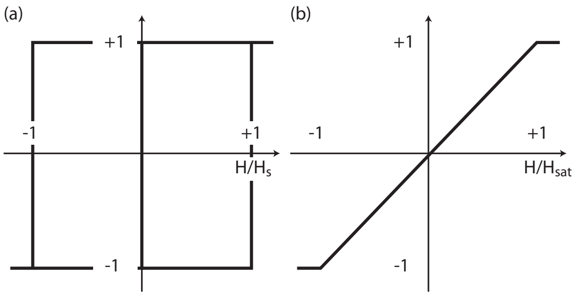

Figure 3: Schematic of Hysteresis curves for a single domain with uniaxial anisotropy. (a) shows an easy axis hysteresis curve and (b) a hard axis hysteresis curve

We have seen the overall hysteresis behavior of a typical ferromagnetic sample, and we know that behavior comes from a collection of magnetic domains. Then, one may ask what is the response of a single domain to the magnetic field, since, after all, a single domain is the building block of ferromagnetism.

3.3.1 Anisotropy

Usually, spins in a ferromagnetic sample prefers lining up in a certain direction. The preference is called magnetic anisotropy and it exists in various forms. From the application point-of-view gaining control over a magnetic thin film's anisotropy is extremely important. For example, hard drive densities increased significantly after out-of-plane magnetization easy-axis was realized in thin magnetic films. Magnetic anisotropy has different strengths and the magnetic anisotropy constant is a measure of this. Anisotropy has a strong influence on the shape of hysteresis loops as shown in fig. 3. There are generally two aspects of anisotropy, one by the lattice structure and another by shape of the sample:

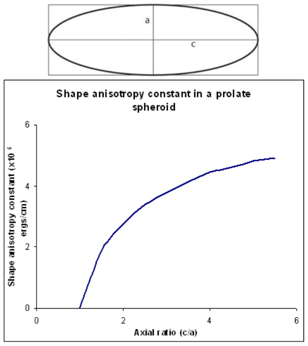

Figure 4: The shape anisotropy of a prolate spheroid according to its symmetry axis[6].

1. An anisotropy caused by the crystalline structure of the material is called the **magnetocrystalline anisotropy**. Depending on the material, it either lies along planes where lattice sites are closest or furthest away. With extreme hand-waving, this phenomena can be understood as the interaction strength of neighboring lattice sites are different along the crystal planes. For example, in iron with cubic crystal lattice, the magnetization prefers directions parallel to the edges of the cube ($\pm xyz$-directions) and in Nickel, the preferred axes are the diagonals. This type of anisotropy can be neglected in polycrystalline or amorphous films [5]. In polycrystalline films, the

sample consists of small clusters oriented at random direction and thus, the average magnetocrystalline anisotropy is zero. In contrast, the atoms in different unit cells are slightly bounded in amorphous films, causing a inter-atomic anisotropy. This mechanism may account for the in-plane uniaxial anisotropy in our sample, which could possibly caused by the growth condition.

2. If the sample's shape is not circularly symmetric then it will experience **shape anisotropy**. This anisotropy attempts to minimize the energy of the magnetic field applying to the sample. The magnetization would prefer to lie along the long side of the shape. In thin films, shape anisotropy causes the easy axes to lie in-plane as out-of-plane magnetization would cause a high density of flux lines [5]. The shape anisotropy can be evaluated analytically only in a few cases, such as infinite thin films or elliptical shapes. For example fig. 4 illustrates the influence of an elliptical shape on the anisotropy.

3.3.2 Stoner-Wohlfarth model

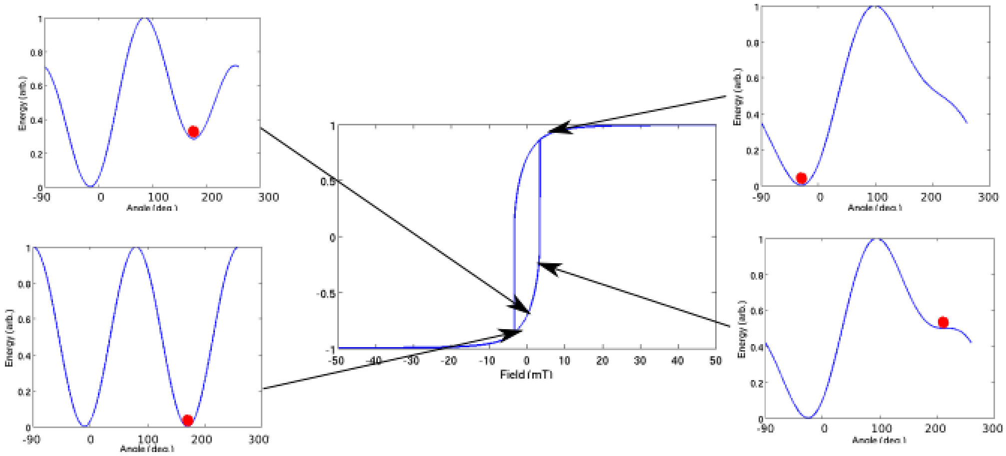

Figure 5: Energy density as function of magnetization angle at different external magnetic fields. The external field is applied at 45° and the easy axis is parallel to 0°. The red dot illustrates the angle of the magnetization, i.e, the local energy minimum.

The Stoner-Wohlfarth model is a simple phenomenological model for the energies and hysteresis loops of a magnetic particle. This model assumes a small magnetic particle which is uniformly magnetized (no domains, all moments parallel). The energy density, U, of such system with uniaxial anisotropy in external magnetic field H is:

$$U = \frac{dE}{dV} = K_u \sin^2(\varphi) - \mu_0 H M_s \cos(\varphi - \theta) \tag{3}$$

where K_u, φ, θ, μ_0 and M_s are uniaxial anisotropy constant (J/m^3), direction of magnetization, direction of external magnetic field, vacuum permeability and saturation magnetization (A/m). At zero magnetic field ($H = 0$, fig. 5 bottom left), only the first term remains and is fully dominated by the anisotropy. At this state, there exists two equally energetically favorable energy minima (0° and 180°) which is known as the easy-axis of the system, which has been mentioned in previous section. Correspondingly, the energy maxima at 90° and 270° is known as the hard-axis, the least preferable direction. The second term in equation 3 represents the influence of external magnetic field to the magnetization direction which is known as the Zeeman energy. When an external field is applied, the magnetization prefers the orientation parallel to the direction of magnetic field in the absence of anisotropy. These competing energies, anisotropy and Zeeman energy, lead to hysteretic behavior. When the field is slowly increased, the relative depth and location of these potential wells change. However, the magnetization cannot escape the local energy minimum and consequently, the magnetization rotates slowly as seen in fig. 1 and 5. When the field completely annihilates the local minimum, an abrupt magnetization switch occurs and the magnetization rotates to the new global energy minimum. The presence of this uniaxial anisotropy has a strong influence on the hysteresis curve depending on the angle between the easy-axis and external field as shown in fig. 3[4].

4 Magneto optical effects

This chapter concentrates on magneto optical Kerr effect (MOKE). This effect will be used to measure the direction of magnetization and is the basis of the MOKE microscope used in this laboratory experiment. MOKE is a universally used non-linear optical effect to measure the magnetic features such as magnetization and anisotropy.

4.1 Reflections from metallic surfaces (mirrors)

Mirrors typically consists of a thin and smooth silver surface. When a mirror is illuminated, the incident and reflected light have the same angle with respect to the surface normal (law of reflection). The reflection is due to interaction between the free electron cloud and the electric field of the electromagnetic wave (light). When an oscillating electric field is applied to a metal, the electrons oscillate back-and-forth in synchronization to this frequency to minimize the electric field inside the metal. However, oscillating (accelerating) charges create electromagnetic radiation which "create" the reflected light.

4.2 Magneto-Optical Rotation Effects

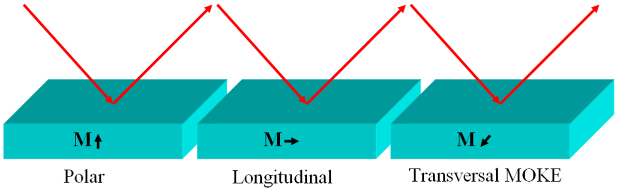

Figure 6: Three geometries of the MOKE[10].

There are three different geometries in which the magneto-optical Kerr effect (MOKE) can be measured. Longitudinal geometry has the magnetization of the sample, reflect plane and plane of incidence in the same plane. This configuration will be used in these experiments as this geometry provides the largest signal. In longitudinal geometry the polarization of the light incident on the magnetic sample is rotated and an analyzer is required to measure the rotation of the reflected light. Transverse MOKE also provides in-plane magnetization information, but the magnetization of the sample is perpendicular to the plane of incidence, and instead the contrast mechanism is a light intensity change. This is a much weaker effect than longitudinal geometry. Finally, polar geometry provides information about the out-of-plane component of the magnetization. In principle, this is similar to longitudinal geometry but does not require a plane of incidence [8, 9].

4.3 Magneto-optical Kerr effect

In this experiment, we will utilize the magneto-optical Kerr effect (MOKE) to measure hysteresis loops. There exists three possible effects when linearly polarized light reflects from a ferromagnetic sample: polarization rotation (Kerr rotation), change in ellipticity (Kerr ellipticity) and/or change in intensity. The strength of these changes depends on the direction of magnetization with respect to the plane of incidence and thus, it can be utilized to measure hysteresis loops of ferromagnetic samples. In this experiment, we will concentrate on the longitudinal Kerr effect where the magnetization is in-plane and there is a finite incident angle ($\sim 10°$).

When polarized light is reflected from a ferromagnetic sample, the electron cloud oscillates similarly as during reflection from a silver-mirror. However, ferromagnetic samples exhibit finite magnetization and thus, the electron cloud is oscillating in a magnetic field. In a simple model, the Lorenz force exerted onto the electrons is

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{4}$$

where q is charge, E electric field, v velocity and B magnetic field. Intuitively, the reflected light does not maintain the incident linear polarization and it is dependent on the magnetization. After some tedious matrix algebra, the Kerr rotation ($\phi \propto M_y$) and ellipticity ($i\phi' \propto M_y$) are proportional to the magnetization. As a result, by measuring the rotation of polarization, it is possible to measure one of the components of the magnetization.

A typical technique to measure the rotation of polarization is the so-called polarizer-analyzer configuration shown in fig. 7. The first polarizer polarizes the incident light which is usually non-polarized, i.e, it contains all polarizations (e.g. halogen bulb). This light is then reflected from the sample and passed through a second polarizer which is known-as the analyzer. According to Malus' law, the transmitted light is

$$I = I_0 \cos^2 \theta \tag{5}$$

where I_0 is the intensity of light after the first polarizer and θ the angle between the initial polarization and the axis of the analyzer. Typically the analyzer-polarizer configuration is held at near extinction angle (90°) with a small skew angle δ. The Kerr rotation of samples is generally low ($\sim 1°$) and thus, we can estimate the resulting intensity using

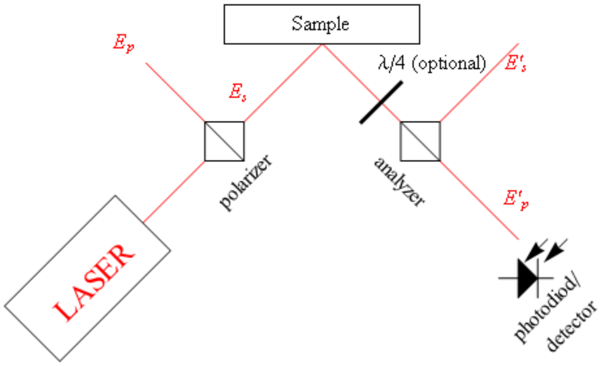

Figure 7: Typical laser based setup used to measure rotation of polarization[11].

Taylor polynomials as

$$I = I_0 \cos^2(\frac{\pi}{2} - (\delta + \phi)) = I_0(\sin^2\delta + \phi \sin 2\delta + \phi^2 \cos 2\delta + \dots) \approx I'_0(1 + \frac{2\phi}{\delta}) \quad (6)$$

where δ is the skew angle and ϕ is the Kerr rotation. Now, the intensity of the transmitted light is proportional to the Kerr rotation (or in general, polarization rotation) and consequently, it is also proportional to the magnetization. However, laser based setups measure the average magnetization over the laser spot-size ($\sim$100 μm) and thus, localized information, e.g, formation of domains, is lost.

4.4 Kerr Microscope

In these experiments you will be using a Kerr microscope which is a method for imaging domains in magnetic thin-film samples as a function of external magnetic field. This microscopy technique allows measurement of localized information of the magnetization at diffraction limited resolution (500 nm) simultaneously over a large area (>40 μm). The measurement system uses an optical microscope with a high-intensity white light instead of a laser and a sensitive CCD camera instead of a photodetector. The schematic in Figure 8 illustrates the light path inside the microscope.

Note that both the external magnetic field and the plane of incidence are fixed during the measurement. We will rotate the easy axis (θ) with respect to the magnetic field by rotating the sample, therefore the external magnetic field and plane of incidence will always lie parallel. The role of the plane of incidence is shown in Figure 9: the magnetizations (**M**) projection onto the axis formed by the plane of incidence is measured along the B-axis of a normalized hysteresis curve.

4.4.1 Contrast enhancement

Once you have the optics correctly set-up it is quickly apparent that contrast is very poor and changes in magnetization can hardly be seen. A background (BG) image is used to enhace the contrast. Here we apply an AC magnetic field which sweeps the magnetization

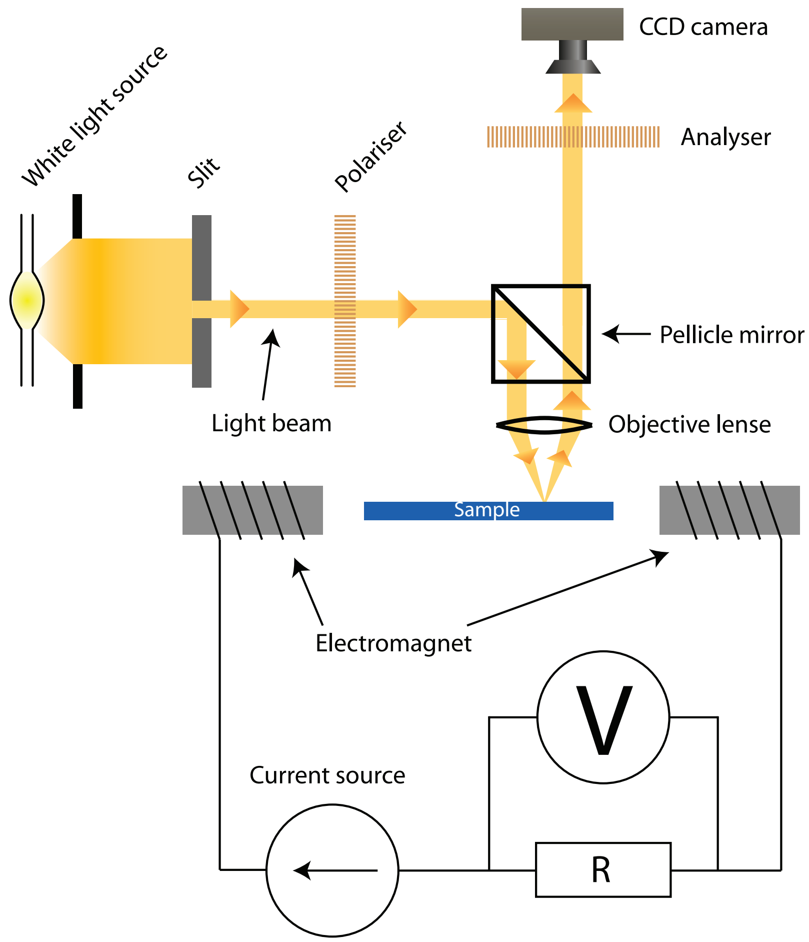

Figure 8: Schematic of side profile of Kerr microscope. The white light source is a high intensity LED lamp and the slit is used to define the incidence angle.

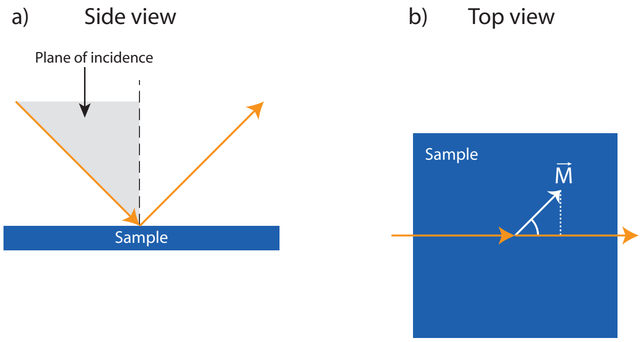

Figure 9: The role of the plane of incidence in longitudinal MOKE. (a) shows the side view of an incident and reflected beam forming a plane of incidence. (b) the top view shows the axis formed by the plane of incidence and the projection of the magnetization vector on to this axis.

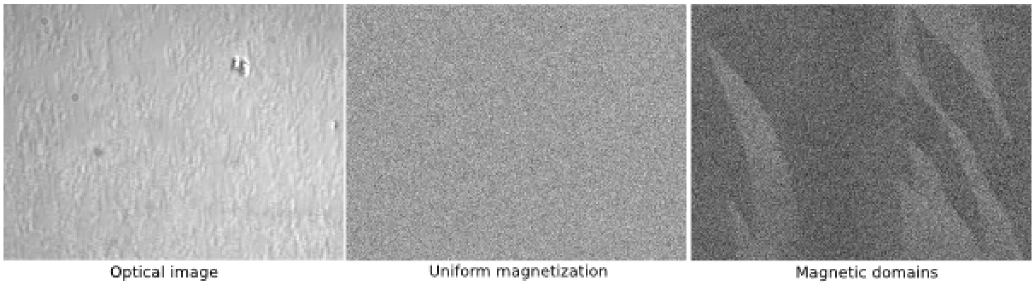

Figure 10: Example of background subtraction process. Left: Image of a highly granular and uneven surface. Middle: Uniformly magnetized state at saturation after background subtraction. Right: Formation of magnetic domains. Notice that the granularity of the surface is no longer visible after background subtraction.

of the sample quickly back and forth (at 10 Hz). A series of images is then captured and averaged which will be used as a background image. As the time of this averaging process is within the few seconds and the magnetization oscillates continuously, the magnetic information is on average zero. Thus, the captured image contains only optical, i.e, non-magnetic, information. More mathematically, the optical information of the surface is I_0 (reflectivity) and the magnetic information is $I_M \propto M_y$. The measured intensity as function of time at angular frequency ω is

$$I(t) = I_0 + I_M(H = H_0 \sin \omega t) \tag{7}$$

where H_0 is constant external magnetic field. If we average over tens of periods, the latter term is approximately zero and the resulting image is pure reflectivity (I_0). Simply subtracting this pure optical information, the final image contains only magnetic information and the intensity is uniform over the imaged area regardless of surface defects (dust) or granularity. Once the BG image has been taken and BG image subtraction enabled, the software automatically subtracts the intensity of each pixel from the BG image before displaying it. This results in an image which is very sensitive to any changes in the sample. By applying an external magnetic field we can force changes to the magnetization (and thus the magnetic domains) which show up in much greater contrast. This improvement after background subtraction is illustrated in fig. 10.

4.5 Faraday Effect

The Faraday effect occurs in transparent materials (such as in optical lenses) in which the magnetic field is parallel to the propagation direction of the light. The rotation of polarization is linear with magnetic field H (up-to very large fields $\gg H_{sat}$) and hence, it affects measurements done here. In the end, the measured intensity from the camera is

$$I = I_0 + I_{\text{Kerr}} M_y(H) + I_{\text{Faraday}} H \tag{8}$$

You will need to remove the Faraday effect from your measurements to obtain correct results. This is done by measuring the gradient of the hysteresis loop when the sample is saturated, i.e, when the first two terms in Eq. 8 are constant, and subtracting this gradient from the hysteresis loop [5].

5 The Experiment

The assistant will help you with setting up the microscope and go through the general procedure. The procedure is briefly explained in this section as well, for future reference. The aim is to find the direction and magnitude of a uniaxial anisotropy in the sample. Therefore hysteresis loops of the sample described below will be measured as a function of external magnetic field angle (θ) using the Kerr microscope.

5.1 The Sample

The sample provided is an amorphous $Co_{40}Fe_{40}B_{20}$ (CoFeB, ferromagnetic) thin film (see side-view of sample in Figure 11). The sample is grown by magneto-sputtering on a Si substrate. It's saturation magnetization is 1.2×10^6 A/m [12, 13].

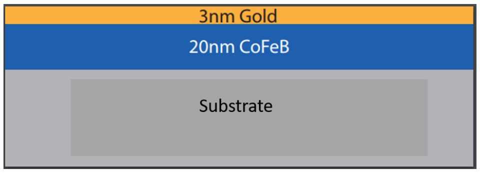

Figure 11: A side-view of the sample which will be used during these experiments.A 20nm CoFeB film is grown on to the Si substrate. 3nm Gold caps the sample

5.2 Setup of the Microscope

To begin with, ensure the following are switched on:

1. Power supply
2. Lamp
3. Microscope
4. CCD Camera
5. Multimeter

The lamp takes about 1 hour to warm up so you will have to wait before hysteresis measurements can be taken. However, alignment of the optics and familiarisation can be done in the meantime:

1. Place the sample onto the sample space.
2. Focus on to the surface of the sample. Since it is flat and smooth it will be hard to distinguish from other defects/dust in the optics. Using the micrometer, move the sample back and forth as you approach the surface and view through the oculars. Once you see defects/spots moving you know you are close to the surface. Find a suitable defect and focus on to that defect.
3. Switch to the back focal plane (BG) and adjust the slit aperature.
4. Switch back to normal view and rotate the magnet so that the magnetic field and optical axis are colinear.
5. Start the Kerr microscope software:
   (a) Take an image and save it by clicking the same image tab.
   (b) Take a background image and take an image of the magnetization.
   (c) Measure the hysteresis by clicking the 'Looper' button. Save looper images for later reference.
6. Repeat above measurements from 0 to 360 degrees in steps of 15 - 30 degrees.
7. The hysteresis curve measurement is saved as a txt-file. The first column is the external magnetic field with units mT (note: units of H are normally A/m) and the second column is the intensity in arbitrary units.

6 Instructions

All the measurements will be done using the Kerr microscope. The aims of the measurement are:

1. For you to learn and understand how magnetization can be imaged using a Kerr microscope.
2. For you to gain understanding and knowledge about magnetic hysteresis measurements and how it is affected by magnetic anisotropy.
3. Determine the direction of the easy and hard axes of the sample.
4. Capture images of the remanent states of the sample as a function of angle.

Important:

- Do not handle the sample with your bare hands. Use the tweezers provided and handle with care to avoid scratching the sample surface. Rubber gloves will also be provided.
- Do not ram the sample with the objective lens or use too much force/speed while focusing.

7 Report

- Explain briefly how ferromagnetism arises (no equations, read from a book or other proper resource).
- Explain briefly the main types of magnetic anisotropy.
- Explain qualitatively how the microscope works and how MOKE provides contrast.
- Remove Faraday effects from the measurements and normalize the Kerr signal in your data from -1 to 1. Why is it best to normalize the Kerr signal?
- Plot remanent magnetization M_r and coercivity field H_c versus the sample angle θ for the sample. Derive an equation for M_r using the definition of a hysteresis loop and Stoner-Wohlfarth model. Does shape anisotropy affect the sample and why?
- Describe the main magnetization reversal processes. What is the preferential direction of the domain walls and why? There are no domains visible in the experiment at certain orientations of the sample. What is the origin of this phenomena? (The figure of domain walls will be given in case not obvious during the experiment.)
- Calculate K_u, the anisotropy constant for you sample by calculating

  $$\frac{dE}{d\varphi} = 0, \tag{9}$$

  which is the energy minimum of the system. Hint: It can be assumed that coherent rotation occurs around $H = 0$. Measure the gradient around $H = 0$ from your experimental data. Using Stonerg-Wohlfarth model and the definition for the hysteresis loop, show that the measured hysteresis loop along the magnetic hard axis is linear (similar to Fig. 3b). You have now derived a formula between the slope and the anisotropy constant K_u. Caution: the definitions of the angles in Stoner-Woflfarth model ($0^\circ \upuparrows$ e.a.) and the Kerr microscope ($0^\circ \upuparrows \mathbf{H}$) are different. Thus, you should be very careful with the angles when comparing Stoner-Woflfarth and experimental results.

8 Prerequisite Questions

1. Try to draw the hysteresis loop with magnetic field i) along the easy axis, ii) 45° to the easy axis, ii) 90° to the easy axis.
2. What is a plane of incidence?
3. What is a linear polarized light?
4. Explain how a polarizer-analyzer set-up be used to detect a rotation in polarization of linearly polarized light by the magnetization.

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Dictionary

Polarisation	Polarisaatio
Analyser	Analysaattori
Plane of incidence	Saapumistaso
Demagnetize	Demagnetoida
Magnetization	Magnetoituma
Hysteresis	Hystereesi
Magnetic domain	Magneettinen alue
Anisotropy	Anisotropia
Thin film	Ohutkalvo
Exchange interaction	vaihtovuorovaikutus
Stress	Jännitys
Strain	Rasitus
Remanence	Jäänösmagnetismi
Easy axis	Helppo akseli
Magnetoelastic	Magnetis-elastinen
Slit	Rakoaukko
Saturation magnetization	Saturaatiomagnetismi
Coherent rotation	Yhtenäinen keirtyminen
Signal-to-noise ratio	Kohinasuhde
Nucleation	Ydintyminen
Longitudinal	Pitkittäinen
Transverse	Poikittainen