Abstract

The Magnetic Properties of Permalloy Antidot Arrays

By Jeremy R. Neal

This account investigates the anisotropy of magnetic thin films of permalloy, Ni$_{80}$Fe$_{20}$, which contain periodic arrays of lithographically defined antidot holes. These samples are studied by means of magneto-optical Kerr effect (MOKE). Detailed in-plane anisotropy data is given which indicates that the symmetry present in the hole pattern controls the formation of easy and hard axes in the samples. As well, an atomic force microscope (AFM) and magnetic force microscope (MFM) analysis is undertaken. Finally, OOMMF, a micromagnetic simulation program, is used to theoretically verify our experimental MOKE results, as well as to simulate the remnant field domain structure of an antidot sample.
The Magnetic Properties of Permalloy Antidot Arrays

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1 Introduction

1.1 Research Incentive

Magnetic thin films are primarily used as a recording media for computer hard drives. This industry continually is trying to achieve higher storage densities by creating new magnetic materials with a greater storage potential. The antidot samples presented in this thesis are a new material which may help to satisfy this goal.

Most previous work with magnetic thin films has concentrated on creating smooth uniform films. Novel materials are created for example by coupling a ferromagnetic layer to an antiferromagnetic layer, which serves to create a more stable media\(^1\). Recently however, attention has shifted to creating patterned magnetic materials. Here, some type of periodic structure is created in the thin film to alter its magnetic properties.

Thin films store information by magnetizing a particular area in the desired direction. By decreasing the size of the region magnetized, you can therefore increase the storage density. When these regions get too small though, they can interact with each other and become demagnetized. As well, these materials are more susceptible to thermal effects. The samples studied here try to reduce interactions between neighboring regions by adding small holes to the material to separate each region. These materials consequently are described as antidots samples.

Our antidots samples consist of a thin film of ferromagnetic permalloy deposited onto a nonmagnetic substrate. Then using a photolithography technique, small holes are created which penetrate through the permalloy layer to create a “negative” structure.
These holes serve as a region with no magnetization, and work to shield neighboring regions from each other magnetically.

A competitor to antidots are patterned magnetic materials with raised sections of ferromagnetic material surrounded by a nonmagnetic region to make a “positive” structure. This serves the same purpose of reducing interactions between neighboring regions as in antidot samples. Either material may be able to achieve higher storage densities than have previously been possible.

Several major hurdles still remain before patterned magnetic materials become commercially viable. The first being that they are very costly and time consuming to produce using current methods. There are no self-assembly techniques available as of yet that could reduce manufacturing costs. As well, the materials and processes which take place within them are not yet completely understood. Clearly more research is needed before patterned magnetic materials come to market. This account will explore the changes that take place in our thin films with the addition of the antidot holes. The results will be verified theoretically with several computer simulations.
2 Background and Theory

2.1 Origins of Magnetism

As a note, the terms spin, moment, and dipole are used interchangeably throughout this text. They all refer to the net magnetic moment of an individual atom unless otherwise noted.

Two properties of the electrons that make up an atom contribute to the magnetic moment of that atom. These are the orbital and spin angular momenta of the electron. The magnetic moment of the atom then determines its magnetic properties. The nucleus also has a small magnetic moment, though it is insignificant when compared to the moment contributed by the electron.

Classically, electrical charges traveling through a loop give rise to magnetization. This is analogous to an electron orbiting around the nucleus or a current traveling through a wire loop. For charge sweeping out an area $\vec{A}$ with current $I$, the magnetic moment, $\vec{\mu}$, is given by

$$\vec{\mu} = I\vec{A}$$

Quantum mechanically, the spin of the electron contributes to the magnetic dipole moment. The magnetic moment contributed by a single electron spin is called the Bohr magneton, $\mu_B$, and has been experimentally and theoretically found to be given by the expression

$$\mu_B = -\frac{e\hbar}{2m_e c}$$

$$= 0.927 \times 10^{-20} \text{ erg} / \text{ Oe}$$
where \( m_e \) is the electron mass, \( e \) is it’s charge, and \( c \) is the speed of light. For an atom, the total spin is given by the quantum number \( S_v \). The orbital angular momentum from the electrons’ motion about the nucleus is given by the quantum number \( L_v \). The total angular momentum vector, \( J_v \), is given by

\[
J_v = L_v + S_v
\]

In finding the total magnetic moment of the atom, it is necessary to introduce another quantity called the spectroscopic splitting factor or Landé g factor. This is due to the fact that the spin angular momentum is roughly twice as effective at contributing to the magnetic moment than the orbital angular momentum. The total atomic moment is thus given by

\[
\mu = g \frac{eh}{2m_e c} J_v
\]

For an atom with only orbital angular momentum, \( J_v = L_v \) and \( g = 1 \). For only spin angular momentum, \( J_v = S_v \) and \( g = 2 \). For other atoms \( 1 \leq g \leq 2 \).

The atomic dipole moment can also be written as

\[
\mu = -\gamma h J_v
\]

where \( \gamma \), the gyromagnetic ratio, is given by

\[
\gamma = -\frac{ge}{2m_e c}
\]

The magnetization, \( \bar{M} \), of a sample is defined as the vector sum of all the individual atomic moments over the sample volume, \( V \), or

\[
\bar{M} = \frac{\Sigma \mu_i}{V}
\]
Several other concepts will be used later in this thesis. For a sample placed in an external field, $\vec{H}$, the magnetic susceptibility, $\chi$, is defined as

$$\chi = \frac{M}{H}$$

It is also useful to introduce a quantity called the magnetic induction, $\vec{B}$. It is given by

$$\vec{B} = \vec{H} + 4\pi \vec{M}$$

### 2.2 Types of Magnetism

#### 2.2.1 Diamagnetism

Since every electron has both spin and orbital angular momentum, it will also possess a magnetic moment. This does not, however, mean that every atom will have a net magnetic moment. In the case that the electrons orient themselves so that their moments cancel, the atom as a whole will have no net moment. This is the case for a diamagnetic material\(^2\).

![Diagram of electron in orbit](image)

**Figure 2.1** An electron in an external field, $\vec{H}$, will create an induced field, $\vec{m}$, according to Lenz’s Law. $\vec{H}$ and $\vec{m}$ are perpendicular to the plane the electron travels in.

An electron in orbit is analogous to a current traveling around a resistanceless wire, as shown in Figure 2.1. When a changing external magnetic field $\vec{H}$ is applied, according to Lenz’s Law, a current is set up which opposes the direction of changing field\(^3\). This is accomplished by a slowing of the electrons orbital speed. This reaction to an external
field is known as a diamagnetic response. All magnetic substances share this response. In a diamagnetic material, since there is no net moment to offset the response, it actually exhibits negative magnetism. Thus a diamagnetic substance is defined as having $\chi < 0$, as well as $|\chi| << 1$.

2.2.2 Paramagnetism

A paramagnetic substance consists of atoms that have a net magnetic moment. In the absence of an applied magnetic field, the moments are oriented randomly due to thermal effects. In the presence of a field though, the moments weakly interact and partially align along the field direction. Thermal effects still prevent the moments from aligning completely. Thus a paramagnet will have $\chi > 0$, but $\chi << 1$.

Molecules and atoms with unpaired electrons will always have a net moment, and thus be paramagnets. As well atoms with partially filled inner shells are paramagnetic. Examples of paramagnetic substances include rare earth and actinide elements, molecular oxygen, and transition metal elements$^2$.

2.2.3 Ferromagnetism

Ferromagnetic substances are of the most interest with regard to this thesis because the antidot samples studied are ferromagnetic thin films. Even in the absence of an applied magnetic field, a ferromagnet will have a net magnetic moment. Exchange interactions between dipoles in a ferromagnet are responsible for this. This has not been the case for the materials already discussed.
The individual atomic moments in a paramagnet may be larger than in a ferromagnet, but since they don’t interact, as a whole the sample will have no net magnetic moment. Exchange interactions cause individual atomic moments in a ferromagnet to align. This interaction, between dipoles $i$ and $j$ with spins $\vec{S}_i$ and $\vec{S}_j$, is governed by the relationship

$$E = -2J \vec{S}_i \cdot \vec{S}_j$$  \hspace{1cm} [1]

where $E$ is the exchange energy, and $J$ is called the exchange integral and is related to the overlap of the neighboring atomic charge distributions. This equation is called the Heisenberg model. When $J$ is positive, the two spins will be in a minimum energy state, when aligned parallel, as seen in Figure 2.2. This is the interaction which gives rise to ferromagnetism. If $J$ is negative, the spins will anti-align, and the material will be antiferromagnetic, which will be discussed in Section 2.3.4.

**Figure 2.2** Arrangement of dipoles in a ferromagnetic material. Due to exchange interactions, neighboring dipoles all align, giving the sample a net magnetic moment.

Ferromagnets, because they have large net moments, consequently have large positive susceptibilities. The susceptibility of a ferromagnet can be thousands of times larger than a similar paramagnetic sample.

Thermal effects, as in a paramagnetic sample, oppose the spontaneous ordering of atomic moments in a ferromagnetic sample. This effect increases with increasing temperature. Thus above a certain point, called the Curie temperature, a ferromagnet will...
behave like a paramagnet. For iron, cobalt, and nickel, the Curie temperature is far above room temperature.

This theory explains why it is possible to have a piece of iron which acts as a permanent magnet at room temperature, though it doesn’t explain why it is also possible to have an unmagnetized piece of iron. This can be explained by the fact that some ferromagnetic substances internally split themselves into domains, as shown in Figure 2.3.

Figure 2.3 Domain structure in a ferromagnetic sample. Adjacent regions are magnetized to saturation, though in different directions. The total magnetization of the sample is zero because all the magnetization vectors cancel. Boundaries between domains are known as domain walls.

Each domain in a ferromagnetic sample is magnetized to saturation, though since the magnetization direction of each domain is randomized, the sample as a whole will have no net magnetization. Domains form in an effort to lower the magnetic energy of the sample. The magnetic energy of a sample with N domains is approximately $\frac{1}{N}$ of the same sample without any domains. The process of dividing into domains stops when the energy required to add another domain wall exceeds the reduction in energy obtained by adding another domain.
Figure 2.4 Orientation of atomic dipole spins in a 180° domain wall. Regions I and III are magnetized in opposite directions, with a gradual transition occurring in region II. This transition normally takes place over several hundred atomic moments.

The boundary between domains is known as a domain wall. The transition between adjacent domains is not immediate, but spread out over a series of dipoles as seen in Figure 2.4. This gradual rotation of dipoles between adjacent domains further reduces the energy of the sample. The exchange energy, \( E \), between adjacent dipoles is given by equation [1]

\[
E = -2 JS^2 \cos \theta \quad [1]
\]

where \( \theta \) is the angle between adjacent dipoles. \( J \) and \( S \) are as defined earlier. The series expansion of \( \cos \theta \) is

\[
\cos \theta = 1 - \frac{\theta^2}{2} + \frac{\theta^4}{24} - ...
\]

Ignoring terms larger than \( \theta^2 \) and substitution into equation [1] gives

\[
E = JS^2 \theta^2 - 2JS^2
\]
Thus, the exchange energy between neighboring dipoles varies as $\theta^2$, rather than as $\theta$. The lowest energy state is when the domain wall is infinitely wide with the smallest possible angle between adjacent dipoles. The anisotropy energy, which will be explained in detail later, increases as domain walls widen and imposes an upper limit on domain wall width.

In a ferromagnetic sample, there also exists a demagnetizing field, as illustrated by Figure 2.5. As shown, a bar magnet has field lines which start at the north pole and end at the south pole. These field lines exist inside of the magnet itself, where they oppose the direction of overall magnetization. This field acts to demagnetize the magnet.

![Figure 2.5 Demagnetizing field of a bar magnet. The overall magnetization points to the right, though the poles create an internal demagnetizing field which points left and reduces the overall magnetization.](image)

Inside the magnet, the demagnetizing field, $H_0$, acts in the opposite direction from the magnetic field, $M$. Thus, in the absence of any other external fields, the magnetic induction is given by

$$B = -H_0 + 4\pi M$$

The demagnetizing field is always smaller than $4\pi M$, so $B$ will be positive. Outside the magnet, $B = H$ as one would expect. It is a very involved process to find the magnitude of
the demagnetizing field in even the simplest cases. In the same material, it will be stronger along the short axis than the long axis. The demagnetizing field is present in all ferromagnetic samples.

2.3.4 Antiferromagnetism

The moments in an antiferromagnet experience exchange interactions similar to a ferromagnet. In this case although, the lowest energy state occurs when neighboring dipoles anti-align, as shown in Figure 2.6. Antiferromagnets have therefore no net atomic moment and small positive susceptibilities.

![Figure 2.6](image)

**Figure 2.6** Orientation of neighboring dipoles in an antiferromagnetic sample (side view of a BCC lattice). The lowest energy configuration for antiferromagnetic materials occurs when rows of dipoles anti-align. The sample has no net magnetization.

As is the case with ferromagnets, an increase in temperature of an antiferromagnet will increase its’ disorder, resulting in it behaving like a paramagnet. The critical temperature this time is called the Néel temperature. This temperature also corresponds to the point of largest susceptibility.

Most antiferromagnetic substances are ionic compounds including oxides, chlorides, and sulfides. The Néel temperature of an antiferromagnet is quite often far below room temperature. Exchange biased read-write heads are one application of antiferromagnetic materials.
2.3 Magnetic Hysteresis

We will now look at what happens to a ferromagnetic sample which is placed in a changing magnetic field. The sample magnetization traces out a hysteresis loop, as can be seen in Figure 2.7. Starting at Point 1, the sample has no initial magnetization because domains are present. As the external field is increased, the magnetization of the sample will gradually increase, following what is called the virgin curve\(^2\). At Point 2, the sample has reached its saturation value. Here, the sample consists of one large domain whose magnetization is aligned with the external field. A further increase in the field will not result in an increase in the sample’s magnetization. If the field is then decreased, the magnetization will persist. Point 3 is known as the remnant magnetization, which is often given as a percentage of the total magnetization. At Point 4, the reversed external field is finally strong enough to “coerce” the sample’s magnetization to begin to change directions. The external field present when the sample hits zero magnetization, denoted by Point 5, is called the coercive field, or \(H_C\). At Point 6, the sample once again reaches saturation, though in the opposite direction from before. If the field is now increased, the magnetization will return back to Point 2. The sample will only return to Point 1, zero magnetization, if a rapidly oscillating magnetic field is applied. Hysteresis arises largely from anisotropy present in the material, which will be discussed in Section 2.4.
Figure 2.7 Sample magnetic hysteresis loop for a ferromagnetic material. The curve from points 1 to 2 represents the virgin curve. Other numbers indicate specific points of interest in the magnetization reversal process.

The virgin curve will now be considered in more detail. It is divided into three separate parts as indicated by the Roman numerals in Figure 2.7. Part I starts at zero magnetization and has a relatively constant slope, usually given by \( \frac{\partial M}{\partial H} = \chi_0 \). This portion of the curve is reversible because if the external field is lowered, the magnetization will approximately retrace the curve backwards.\(^4\)

Part II of the virgin curve is irreversible. Here, the sample magnetization increases rapidly with increasing external field. Often, \( \frac{\partial M}{\partial H} \) can exceed \(10^6\) over this region. In the third region, the sample approaches saturation magnetization. The slope levels off and eventually approaches zero. This portion of the curve is reversible to a large extent.\(^3\)

It is of interest to look at what is happening at the domain level within a ferromagnetic sample during the process of generating a hysteresis loop. As in Figure 2.8, the sample initially starts with no net magnetization at \( H = 0 \). As the field is increased in a given direction, the domains which are aligned with the field will increase in size. All other domains lose area. Eventually, all dipoles in the sample align with the external field, and
the magnetization of the sample is saturated. The process by which the walls between adjacent domains shift is called domain wall motion.

Figure 2.8 Response of domains in a ferromagnetic material to an external field. Small arrows indicate the direction of magnetization within each individual domain. The sample starts with no net magnetization at $H = 0$. With increasing field, the domains that are aligned with the field increase in size while others shrink. Eventually, the domains disappear when all the moments in the sample are aligned with the external field.

Once the sample has reached its saturation magnetization, if the field is decreased, domains structures will not reform. Instead, one large domain wall will form which moves across the entire sample. If a sufficient field is applied opposite the original direction, the sample will once again reach its saturation magnetization in this direction. Domains will only reform if a rapidly oscillating magnetic field is applied, as was the case earlier. Figure 2.8 is a simplification of what is happening in an actual sample. In the samples studied in this thesis, there are several hundred to several thousand domains present. Still, the process is quite similar.
Other than domain wall motion, there is one more process by which the magnetization direction of a ferromagnetic sample can change. This is called domain rotation and is shown in Figure 2.9. Fairly strong fields are needed to magnetize a sample in this way, whereas domain wall motion generally takes place at lower fields. Once again, at saturation there is no domain structure present. Both domain reversal and rotation can occur in different areas of a sample simultaneously.

\[ H = 0 \quad \rightarrow \quad M = 0 \]

\[ H \quad \rightarrow \quad M > 0 \]

\[ H \quad \rightarrow \quad M = M_s \cos 45 \]

\[ H \quad \rightarrow \quad M = M_s \]

**Figure 2.9** Domain rotation in a ferromagnetic sample. Domains partially aligned with the external field increase in size until eventually only they persist. Further increasing the external field causes the sample magnetization to rotate until it is saturated along the field direction$^2$.

The shape of the hysteresis loop can tell us much about the sample. As well, measurements of the coercive field, percent remanence, and saturation magnetization can help determine if the sample may have commercial applications. Materials with a large energy product, which is defined as the coercive field multiplied by the saturation magnetization, make good magnetic recording media.
2.4 Magnetic Anisotropy

The term anisotropy simply means that the properties of a sample depend on the direction of measurement. Magnetic anisotropy will be an important topic in the remainder of this thesis. Knowledge of the anisotropy of the material reveals details about the atomic structure and molecular arrangement of the material. There are several different sources of magnetic anisotropy. These will be discussed in the following sections.

2.4.1 Crystalline Anisotropy

Crystalline anisotropy is the only type of anisotropy that is inherent to the material in question. All other types of magnetic anisotropy are induced in the material. As shown for a simple cubic lattice in Figure 2.10, there are three principle directions over which the magnetic properties of the sample will vary. The direction upon which the sample most easily reaches its saturation magnetization is known as an easy axis. The direction upon which it is the hardest to reach saturation magnetization is a hard axis, and all other directions are intermediate or medium axes.
Crystalline anisotropy has its origins in the spin-orbit coupling\(^1\). The orientations of orbits in a crystal lattice are fixed by the lattice. When an external field tries to change the spin direction of an electron, it also tries to change the orbital direction due to spin-orbit coupling. This is resisted by the orbit-lattice coupling. Thus, an energy, the anisotropy energy, is required to overcome the spin-orbit coupling and rotate the spin away from the easy axis.

There exist internal fields within a ferromagnetic sample which direct the magnetization along a certain axis, called an easy axis. This direction is the most energetically favorable and it is easier to magnetize the sample along this axis. For a sample which contains domains, each domain has a favored direction which its’ magnetization will lie upon.

If a strong magnetic field is applied in a direction other than along the easy axis of a sample, the magnetization of the sample will rotate in the direction of the external field. The energy it takes to rotate the magnetization from an easy to a hard direction is known as the anisotropy energy.

\(^1\) Spin-orbit coupling refers to the interaction between the spin of an electron and its orbital motion, which causes a splitting of energy levels.
Crystalline anisotropy energy is expressed in terms of constant coefficients, $K_0$, $K_1$, etc., which have units of energy density, and is given by

$$E = K_0 + K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2(\alpha_1^2 \alpha_2^2 \alpha_3^2) + ...$$

where if $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the angles that M makes with the principle cubic axes, then $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the cosines of these angles. Terms larger than $K_2$ are generally very small, and hence are normally dropped. As well, $K_0$ is a constant term and is often ignored because we are interested in the change in energy as the sample is rotated with respect to the external field.

As a note, any sample which has one easy axis is referred to as having uniaxial anisotropy. Two easy axes indicate biaxial, or two-fold, anisotropy and so forth.

2.4.2 Shape Anisotropy

The demagnetizing field is responsible for causing shape anisotropy. As discussed earlier, the demagnetizing field is stronger along a short axis than along a long axis of a material. Thus, the sample will more easily be magnetized along the long axis, since the demagnetizing field opposes the magnetization of the sample. We say that the sample exhibits shape anisotropy in this case. Thin films, which will be covered in a later section, exhibit a large demagnetizing field out of the plane of the sample since they have limited thickness. Thus causes the spins to only rotate in the plane of the sample.

2.5 Thin Films

Magnetic thin film samples have been studied extensively since the 1950’s. They typically consist of a thick nonmagnetic substrate covered by very thin separate layers of
different types of magnetic materials. These thin film layers, usually several nanometers thick, may alternate back and forth between ferro-, antiferro-, and nonmagnetic materials. This changes the nature of the coupling between layers and varies the magnetic properties of the sample\(^1\).

Since thin films have a large surface area for a given volume of material, they sometimes exhibit properties which are much different than a bulk sample of the same material. The spins of electrons on the surface or at an interface of a thin film material behave differently than those electrons inside the material. Since a much greater percentage of electrons are on the surface or interface in a thin film, we expect that the sample would have different magnetic properties than a bulk material. As well, the energy and width of domain walls in thin film samples vary greatly from those in bulk samples\(^5\).

Thin films also offer a way of studying properties which would be hard to study in bulk form. For example, strain induced in thin films by epitaxial growth on a crystalline substrate can form stable materials which correspond to high pressure or high temperature phases in the bulk material\(^4\). Such materials may also exhibit properties not seen in the bulk material and offer a unique opportunity to study new magnetic phenomena.

In a thin film sample, the type of nonmagnetic substrate used can also have an effect on the properties of the material\(^1\). The substrate typically may be glass, silicon, or some ceramic material. Crystalline thin films are generally deposited on crystalline substrates. The lattice spacing between the sample and the substrate may be the same or different. By creating a lattice mismatch between the substrate and the sample, it is possible to
grow a thin film with a different crystalline structure or lattice constant than it would normally have as a bulk material.

The main application of magnetic thin film samples is as a media for computer recording. Indeed, most data storage today uses magnetic thin films of one sort or another. New materials are constantly being developed in the race to store more information in a given volume.

2.6 Kerr Effect

The Kerr effect was discovered by John C. Kerr in 1875. It is characterized by causing a rotation of the polarization of monochromatic linearly polarized light upon reflection from a ferromagnetic material. The reflected beam also becomes elliptically polarized. Ellipticity refers to a condition where the electric field vector of the polarization traces out an ellipse in a plane normal to the direction of propagation. The Kerr effect is different than other magneto-optical effects in that its size is proportional to the thin film magnetization and it disappears above the Curie temperature. There are three distinct types of Kerr effects, the longitudinal, polar, and transverse effects, which are illustrated in Figure 2.11. The difference in the type of effect depends on the orientation of the magnetization of the sample relative to the polarization of the incident beam of light. The p-component of the lights’ polarization lies in the plane of incidence in all three cases.
Figure 2.11 Diagram illustrating the three different Kerr effects. The difference in type depends only on the direction of magnetization of the ferromagnetic surface relative to the polarization of the incident beam. Labeled arrows indicate the polarization direction.

In the longitudinal Kerr effect, the plane of incidence of the laser light is parallel to the magnetization of the sample. This configuration produces the smallest rotation in the polarization of the light of the three types of effect. As well, the amount of rotation depends on the angle of incidence of the light source. The longitudinal Kerr effect is used in this thesis.

The transverse Kerr effect differs from the longitudinal effect in that the plane of the incident light is perpendicular to the magnetization of the ferromagnetic surface. This orientation produces a slightly larger polarization rotation than the longitudinal Kerr effect.

The polar Kerr effect is the most different of the three effects. Here, the magnetization of the sample is normal to the surface. This effect gives the largest polarization rotation of the three cases, which is on the order of three to four times that of the longitudinal effect.
Kerr effect. Large fields are required in this geometry because thin film samples have a large out-of-plane demagnetizing field.8

Figure 2.12 Diagram showing the Faraday effect. Here light passes through the sample and experiences a polarization rotation. The magnetization is normal to the surface.

The polar Kerr effect is very similar to the Faraday effect, which is shown in Figure 2.12. The difference being that the light passes through the sample and undergoes a polarization rotation in the Faraday effect. Because the light has to be transmitted through the material, the metallic layer is limited to around 1000 Å. In principle, the Faraday effect is no different than the Kerr effect.

The largest measurable polarization rotation due to the Kerr or Faraday effects is on the order of one or two minutes or arc9. Very sensitive experimental techniques are required in order to measure this small change in polarization direction.

There are two general types of Kerr effect experiments10. The first utilizes a variable wavelength light source and are described as spectroscopic experiments. The goal of these studies is to determine the frequency-dependent response of the system. Magnetic circular dichroism is an example of this class of experiments. The second type of experiments utilize a fixed wavelength light source and vary some other parameter, such as sample thickness, deposition method, or angle of the sample with respect to the applied field. Such experiments are the most common and explore magnetic anisotropy, critical
phenomena, and other properties of the samples. The Kerr effect experiment done in this thesis falls into this second general class.

The Kerr effect is due to the spin-orbit interaction of the electron, and was first described by Argyres in 1955. More specifically, the change in polarization associated with the Kerr effect is due to the difference between the Fresnel reflection coefficients for right and left circularly polarized light. A complete derivation of the effect is beyond the scope of this thesis.

The amount of rotation, \( \Phi \), which the polarization receives due to the Kerr effect is given by

\[
\Phi = -\text{Im} \left[ \frac{N_+ - N_-}{N_+ N_- - 1} \right]
\]

with an associated ellipticity, \( E \), of

\[
E = -\text{Re} \left[ \frac{N_+ - N_-}{N_+ N_- - 1} \right]
\]

where \( N \) is the complex index of refraction of the ferromagnetic material. \( N_+ \) and \( N_- \) are then given by

\[
N_- = \sqrt{1 + 4\pi(\alpha_0 + \sigma_0 / i\omega) + i4\pi(\alpha_1 + \sigma_1 / i\omega)}
\]

\[
N_+ = \sqrt{1 + 4\pi(\alpha_0 + \sigma_0 / i\omega) - i4\pi(\alpha_1 + \sigma_1 / i\omega)}
\]

where \( \alpha_0 \) and \( \alpha_1 \) are components of the polarizability tensor and \( \sigma_0 \) and \( \sigma_1 \) are components of the conductivity tensor. All these values are constants. Also, \( \omega \) is the laser frequency. Thus, the quantity appearing in equations [2] and [3] above reduces to
\[
\frac{N_+ - N_-}{N_+N_- - 1} = (-4\pi) \left( \frac{\sigma_1/\omega}{(n - ik)((n - ik)^2 - 1)} \right) + i\alpha_1
\]

where \( n \) is the real part of the index of refraction and \( k \) is the imaginary part. The Kerr rotation and ellipticity of a magnetic sample are directly proportional to the magnetization of that sample\(^{11}\). Permalloy, the material used in the antidot samples studied in this thesis, is made up of iron and nickel. For these materials, \( \alpha_1 \) and \( \sigma_1 \) are

\[
\begin{align*}
\text{Fe: } &\quad \sigma_1 \approx 3.1 \times 10^{12} \text{ sec}^{-1} \\
&\quad \alpha_1 \approx 1.7 \times 10^{-2}
\end{align*}
\]

\[
\begin{align*}
\text{Ni: } &\quad \sigma_1 \approx 30.0 \times 10^{12} \text{ sec}^{-1} \\
&\quad \alpha_1 \approx 4.3 \times 10^{-2}
\end{align*}
\]

These values are listed for the sake of completeness, though they will not be used.

One disadvantage of Kerr effect experiments is that they cannot give any information about the absolute magnetization of the sample. This is possible with other experiments, such as with a properly calibrated vibrating sample magnetometer. Instead, Kerr effect experiments give information about a materials response to a variable external field and directly measures the anisotropy fields inherent to the sample. Anisotropy constants can be determined if a value for the saturation magnetization is known\(^4\). The major advantage of Kerr effect experiments is that they act in a very localized region of the sample (usually 100 µm in diameter with a tightly focused laser) and are able to determine properties that would not be seen with a larger sample.
3 Experiment

3.1 MOKE Setup

The MOKE used for this thesis was set up as shown in Figure 3.1. The thin film samples were placed on a rotating mount which sits between the poles of an electromagnet. By rotating the sample with respect to the external field, it is possible to determine the symmetry of anisotropy present in the sample. Linearly polarized light from the laser strikes the sample and is reflected into the detector. At the sample surface, the Kerr effect causes a rotation of the polarization of the laser light.

![Figure 3.1](image-url) Experimental setup used for the MOKE. The sample is placed on a rotating mount between the poles of the magnet and the experiment is controlled through the GPIB from LabVIEW™.

It is important that the laser used in the MOKE be stable both in intensity and polarization direction. Since this experiment is measuring an intensity change caused by the Kerr rotation, if the laser is unstable in either respect, it will produce incorrect results.
The laser used in this experiment is a $5,000 Spectra-Physic model 117A, which uses feedback to electronically stabilize itself.

The entire experiment is controlled from a computer running LabVIEW™. Signals are sent and received over the GPIB, or general-purpose interface bus. This provides the ability to quickly get accurate data.

3.1.1 Principle of Operation

When the linearly polarized light from the laser strikes the surface of the sample, it experiences a polarization rotation due to the Kerr effect as shown in Figure 3.2. It then passes through a second polarizer and into the detector. Any rotation due to the Kerr effect will result in a change in the intensity out of the second linear polarizer. In practice, the second polarizer is nearly crossed with respect to the direction of polarization of the laser, which is done to improve the signal to noise ratio.

![Figure 3.2](image)

**Figure 3.2** Intensity change caused by the Kerr effect. The Kerr effect rotates the polarization of the laser by an angle $\theta$. The light then travels through a second linear polarizer and an intensity change occurs.

3.1.2 Signal Detection

The amount of Kerr rotation experienced by the laser beam is proportional to the net magnetization of the sample$^{11}$, which can be easily changed by varying the external field.
Thus, we sweep the field, starting at a sufficiently high value, decreasing steadily to the negative of this field, and returning to the original value. The magnet power supply, which varies the field, is not directly controlled by LabVIEW™. Instead, a GPIB signal is sent to a digital-to-analog converter, which in turn sends an analog signal to the power supply. A Hall probe sits between the magnet poles and takes accurate field readings which are sent via the GPIB to LabVIEW™.

For the MOKE to function properly, it is necessary to eliminate any background interference so that only light from the laser is measured. This is accomplished by using a photoelastic modulator, or PEM and a lock-in amplifier. The PEM serves the same purpose as an optical chopper, breaking the beam at a set frequency, and consists of a modulator and a controller. The PEM controller sends a 50 kHz frequency signal both to the modulator and the lock-in amplifier. The lock-in also receives the output from the photodetector. It then filters out any signal which isn’t modulated at the reference frequency from the PEM controller, thus eliminating background interference. The lock-in then sends LabVIEW™ intensity measurements via the GPIB.

A large part of this thesis was writing a new LabVIEW™ program to control the MOKE after a previous version was lost. Many changes were made to improve our data taking ability. A feature was added which allows the user to specify the number of field sweeps to be taken. The data is then averaged, which greatly cuts down on the amount of noise present in the final hysteresis loop. The program automatically also plots the data on normalized axes, saving the user from having to do so manually. A screen shot of the MOKE program is given in Appendix 1.
The procedure used to generate a hysteresis loop with the MOKE is as follows:

1. Mount the sample flat onto the sample holder with non-magnetic grease.
2. Turn on all the equipment (the laser must be on for about an hour before it stabilizes).
3. Adjust the second polarizer so that the output beam is as close to extinction as possible.
4. Move the detector so that the laser is fully striking its active area (the detector position may need to be adjusted as the sample is rotated).
5. Adjust the lock-in settings to match the signal size (some functions must be set through the front panel in LabVIEW™). The lock-in has the best signal to noise ratio in current mode.
6. Adjust the sweep time and number of sweeps through the front panel of LabVIEW™. Higher field ranges require longer sweep times to generate good data.
7. Run the LabVIEW program. Data is automatically displayed when the program finishes and is saved to an Excel™ spreadsheet file.

The sample can be rotated by some angle and this process repeated, starting at step 4, to determine the anisotropy present in the thin film. Typical settings for this experiment are given in Table 3.1. Additionally, the polarization direction of the laser must initially be at 90° to the external field.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Constant</td>
<td>100 ms</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1 - 50 mV</td>
</tr>
<tr>
<td>Dynamic Reserve</td>
<td>Normal or Low Noise</td>
</tr>
<tr>
<td>Number of Sweeps</td>
<td>1 - 5 Sweeps</td>
</tr>
<tr>
<td>Sweep Time</td>
<td>.25 - 1 min</td>
</tr>
<tr>
<td>PEM Wavelength</td>
<td>50 - 300 nm</td>
</tr>
</tbody>
</table>

**Table 3.1** Typical MOKE settings used to generate hysteresis loops.
4 Samples

4.1 Bulk Permalloy

Permalloy refers to a large class of materials containing anywhere between 50 and 80% nickel, with the balance being iron. Permalloy is a magnetically soft material, meaning that it is easy to magnetize and demagnetize. It forms as a face-centered cubic crystal and has a large permeability even at low fields. Permalloy has been studied in great detail for its magnetic properties. It is often combined with small concentrations of molybdenum, copper, or other materials for use in specific applications. Permalloy is commonly used in transformer core fabrication, amplifiers, relays, and magnetic recording heads.

4.2 Antidot Samples

The samples which are being studied for this thesis are described as antidot samples. They are one of a new class of patterned magnetic materials which are being studied as a prototype for new high density recording media. These particular samples were made at the University of Alabama at Tuscaloosa.

The antidot samples consist of a permalloy thin film deposited onto a nonmagnetic silicon substrate. The permalloy used herein consists of four parts nickel to one part iron. It is deposited by a process of dc-magnetron sputtering onto native-oxide silicon (001). The permalloy layer is 40 nm thick. During deposition, a field of 100 Oe was applied in order to create an induced anisotropy in the sample.

After deposition and cleaning, the samples go through the photolithography process. They are first covered with a polymer photoresist and the sample is spun to form an even
thin photoresist layer. A mask, which contains the hole pattern, and the samples are placed in an aligner and are exposed to ultraviolet light. This makes the portion of the photoresist which isn’t covered by the mask soluble. The mask is then removed and the UV-exposed photoresist is dissolved with a solvent. The entire sample is then subjected to a procedure called ion milling in which argon ions are translated over the sample surface. This molecularly removes material from the surface at a uniform rate, creating the antidot holes. Finally, the remaining photoresist is removed with acetone and the sample is finished. During this process, the mask is placed in contact with the sample which gives the necessary resolution to create the antidot holes.

The antidot holes go completely through the permalloy layer and into the silicon substrate. Each hole is approximately 2 µm in diameter, and they are placed in varying square, rectangular, and hexagonal patterns with hole spacings from 3 to 7 µm. Of primary interest to this thesis are the square and rectangular antidot patterns, though a hexagonal array is also inspected.

In order to better characterize the actual antidot samples, an atomic force microscope (AFM) was used to take their images, which can be seen in Figure 4.1. Additionally, a 3-dimensional image of the hexagonal antidot sample can be seen in Figure 4.2. An AFM works by sliding a pointed tip over the sample surface. The tip is attached to an extremely flexible cantilever which has a high resonant frequency. This allows the tip to be in almost constant contact with the surface while causing little damage to the sample. A laser is reflected off the back of the cantilever onto a position sensitive detector, which can determine the tip height at a given time. Piezo-electric elements scan the sample under the tip and an image is generated.
Figure 4.1 AFM images of the antidot samples. Each image is 20x20 µm. Hole spacings are: A 3x3 µm, B 4x4 µm, C 5x5 µm, D 3x4 µm, E 3x5 µm, F 3x7 µm, and G 3 µm hexagonal.

The AFM used to take these images was a Nanoscope III manufactured by Digital Instruments and was used in contact mode. Several interesting pieces of information were gained by this analysis. The first being that the photolithography created holes which not only penetrated through the 40 nm thick permalloy layer, but also through around 60 nm
of the silicon substrate, as shown in Figure 4.3. This should not have an effect on the
magnetic properties of the sample since the substrate is nonmagnetic.

Figure 4.2 3-dimensional image of the hexagonal antidot array. This image was
generated from the same data as the hexagonal sample shown in Figure 4.1.

Figure 4.3 Depth profile for a series of three antidot holes. The holes penetrate through
the 40 nm thick permalloy layer and through 60 nm of the silicon substrate. Note the
different scales on each axis.

A second fact gained from the AFM analysis was that not all the holes in the samples
were round. Instead, they appear to be square, hexagonal, or diamond shaped and vary
from sample to sample, though they are consistent within a sample. What effect this has
on the magnetic properties of our samples is uncertain. The most important information
gained from the AFM images was a precise measurement of the hole sizes and spacings. These values differed slightly from those we had assumed earlier. The measured values are given in Table 4.1.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Hole Size (µm)</th>
<th>Horizontal Spacing (µm)</th>
<th>Vertical Spacing (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 x 3 µm</td>
<td>2.1</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>4 x 4 µm</td>
<td>2.0</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>5 x 5 µm</td>
<td>2.2</td>
<td>5.3</td>
<td>5.4</td>
</tr>
<tr>
<td>3 x 4 µm</td>
<td>2.2</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td>3 x 5 µm</td>
<td>2.2</td>
<td>3.2</td>
<td>5.5</td>
</tr>
<tr>
<td>3 x 7 µm</td>
<td>2.2</td>
<td>3.2</td>
<td>7.2</td>
</tr>
<tr>
<td>3 µm Hexagonal</td>
<td>2.1</td>
<td>3.0 (Nearest Neighbor)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Actual hole spacings and sizes in the antidot samples. These values were measured directly from the AFM images using an image analysis program.

Previous work with these antidot samples has examined several of their properties. Yu et al.\textsuperscript{13} looked at the domain structure by means of a magnetic force microscope (MFM). Images of the sample were taken at different external field levels to show the magnetization reversal process in the individual domains. As well, torque magnetometer data showed that a four-fold anisotropy existed in the 3 x 3 µm antidot array.

Vavassori et al.\textsuperscript{15} used magneto-optic Kerr vector magnetometry (V-MOKE) to investigate the magnetization reversal process as well as domain formation in the antidots samples studied herein. V-MOKE is a variation of MOKE which allows for the determination of the magnetization vector direction as a function of the applied field. They showed that there is an increase in the coercive field and a change in the type of anisotropy present with the addition of antidots to the permalloy films.
5 Results and Discussion

5.1 Experimental Results

5.1.1 Sheet Film

The permalloy sheet film was deposited in the presence of a magnetic field to induce the formation of an easy axis. This creates a uniaxial anisotropy in the sample. Figure 5.1 shows the remnant percentage as a function of in-plane angle for the permalloy sheet film. The existence of only one easy axis at 90° confirms that the sample exhibits uniaxial anisotropy. As well, the remnace percentage varies greatly, ranging from about 18% to nearly 100%.

![In-Plane Remnance](image)

**Figure 5.1** In-plane remnance for the permalloy sheet film. This sample exhibits uniaxial anisotropy with an easy axis oriented at 90°.

A magnetic force microscope (MFM) was used to image the surface of the permalloy sheet film. This process is similar to that of the AFM, though it has the advantage that it is able to show domains within the material. In this case, a 20 x 20 µm area was scanned, and is shown in Figure 5.2. There are no visible domain walls in this image. This does not
indicate that domains aren’t present in the sample since they might be larger than the imaged region.

Figure 5.2 Magnetic force microscope image of the surface of the permalloy sheet film. There are no visible domain walls in the sample indicating that domains aren’t present or they are only visible on a larger scale.

A MOKE hysteresis loop for the permalloy sheet film is given in Figure 5.3. As can be seen the sample exhibits a small coercive field of only about 3 - 4 Oe. More complete data for all the samples studied is available in Appendix 2. MOKE results are reported in terms of the relative magnetization of the sample, though the experiment actually measures the change in relative intensity of the laser beam. As mentioned in earlier, these quantities are directly proportional\textsuperscript{11}, so the comparison is valid.
Figure 5.3 MOKE hysteresis loop for the permalloy sheet film. This loop was taken at 60°. The data indicates a coercive field in the sample of approximately 3 – 4 Oe. Complete data for this sample can be found in Appendix 2.

5.1.2 Square Samples

The three antidot samples with square symmetry exhibited anisotropy which differed from the sheet film. Figure 5.4 shows the in-plane remanence for these samples. All three exhibit biaxial anisotropy, while the sheet film has uniaxial anisotropy. The remnant percentages along the easy axis, at 45°, were nearly the same for all three samples, ranging from around 90% to 93%. Along the hard axis, at 90°, the hole spacing seems to have an effect on the remnant percentage. The experimental results show that the smaller the hole spacing is, the lower the remnant percentage will be. The remnant percentages along the hard axis at 0° nearly match those seen at 90°, which should be expected since the samples are symmetric along these axes.
In-Plane Remnance

![In-Plane Remnance Graph](image)

**Figure 5.4** In-plane remnance for the three square antidot arrays. All three samples exhibit biaxial anisotropy.

MFM images of the square samples indicate the presence of domains, as seen in Figure 5.5. These domains are relatively small in size and vary periodically with the hole pattern. The largest domain occupies the region between the holes with four smaller domains surrounding it which connect the holes.

![MFM Image](image)

**Figure 5.5** MFM image of a square antidot array. Small, wedge shaped domains connect the antidot holes with a single large domain occupying the region between them.
A MOKE hysteresis loop from the 3 x 3 µm sample is given in Figure 5.6. In this case the sample has a coercive field of approximately 20 Oe, which is much larger than that of the sheet film. All the antidot samples exhibited a similar increase, though no correlation was able to be drawn between the value of the coercive field and the antidot hole pattern spacings. The increase is attributed to the holes themselves, which hinder domain wall motion\(^{14}\), thus requiring a larger field for the sample to change its magnetization.

![4 x 4 µm Hysteresis Loop](image.png)

**Figure 5.6** MOKE hysteresis loop for the 4 x 4 µm antidot sample. The data indicates a coercive field of approximately 25 Oe, which is several times that of the permalloy sheet film. A similar increase was seen in all the antidot samples.

### 5.1.3 Rectangular Samples

The rectangular antidot samples, like the square ones, exhibit biaxial anisotropy, as seen in Figure 5.7. Again, along the easy axes at 45° and 135°, the samples have similar remnant percentages, varying generally between 90% and 95%. Along the hard axis, at 0°, the samples have remnant percentages between 60% and 70%, with no definite correlation between hole spacing and percent remnance. Along the second hard axis, at 90°, the remnant percentages are up to 25% larger than along the first hard axis with all three samples between 85% and 90% remnance.
Figure 5.7 In-plane remnance for the three rectangular antidot samples. All three samples exhibit biaxial anisotropy.

Additionally, the rectangular samples show domain formation which varies periodically with the antidot hole pattern. The domains formed in a fashion which is very similar to that in the square samples. An MFM image of the 3 x 4 antidot sample is shown in Figure 5.8.

Figure 5.8 MFM image of the 3 x 4 antidot array. Domains form in a similar manner as seen in the square sample.
5.1.4 Hexagonal Sample

The hexagonal sample provides the clearest explanation as to how the hole pattern affects the in-plane remnance of the antidot samples. Figures 5.9 and 5.10 show the in-plane remnance for the hexagonal sample. We see a six-fold anisotropy with alternating easy and hard axes every 30°. The nearest neighbor directions of the hole pattern, at 0° and 60°, are hard axes, while intermediate axes are easy. This is a trend present in all the antidot samples studied.

![In-Plane Remnance](image)

**Figure 5.9** In-plane remnance for the hexagonal antidot sample. This sample exhibits six-fold anisotropy.
Figure 5.10 Polar Plot of the in-plane remnance for the hexagonal sample with the hole pattern superimposed over the data. All the nearest neighbor directions are hard axes with easy axes between them. The data has been plotted twice to complete the circle.

An MFM image of the hexagonal sample is shown in Figure 5.11. Here, a slightly more complicated domain structure than has been seen previously is present.

Figure 5.11 MFM image of the hexagonal antidot sample. Black circles have been added to show the antidot holes. The domain structure in the hexagonal array is not as clear as in the previous images.
5.2 Micromagnetic Simulations

In order to learn more about the properties of the antidot samples, a micromagnetic simulation program called Object Oriented MicroMagnetic Framework (OOMMF) was used. This program was developed by the Information Technology Lab at the National Institute of Standards and Technology and is a very powerful and versatile program which can simulate almost any micromagnetic situation.

OOMMF initially places individual spins in a uniform grid pattern over the sample. Their initial direction can be oriented in several different ways, including having all the spins pointing in the same direction, forming a vortex domain structure, or pointing in random directions. The program then integrates the Landau-Lifshitz equation using an Adams type predictor-corrector method over a user defined time step. The Landau-Lifshitz equation describes a materials time-dependant response to a magnetic field, and is given by

\[
\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}
\]

where all quantities are as defined earlier. After this process, if the energy of the system is less than the previous step, then the new step is accepted, if not, then the step size is reduced and the procedure is repeated. Once the total energy falls below a predetermined level, the program terminates.

In all cases, the OOMMF simulations were run on antidot samples of size 9.6 x 9.6 \( \mu \text{m} \). Each individual cell, or spin, was 40 x 40 nm. Appropriately sized and spaced holes were placed in the samples as necessary using a masking technique. The initial direction of each individual spin is randomized.
5.2.1 Remnant Field Simulations

As mentioned in Section 2.3, domains do not persist at the remnant state of a magnetic material. In the antidots though, the material separates into domains at the remnant state. This occurs because of the formation of a large demagnetizing field at the hole edge. To minimize this field, and to reduce the overall energy of the sample, it will organize into domains. OOMMF was first used to simulate this remnant state domain structure. To do so, the sample is initially placed in a large external field with its’ spins oriented randomly. OOMMF then runs until the total torque on the system is below a preset value. Once this occurs, the field is reduced in steps and the process repeated. Once the simulation reaches zero field, it stops and the data is saved. A relatively large torque value is used for this part of the experiment to speed up calculations. To then improve the results, a smaller torque value is entered and the system is allowed to continue running. Using this method, it is possible to generate a domain structure that closely mimics the actual domain structure, as determined from the MFM images.
For the $3 \times 4$ µm antidot sample, we see the formation of three distinct domain types, as shown in Figure 5.12. Two of them connect the holes along the long and short axes of the hole mesh with magnetizations oriented at $90^\circ$ to each other. The magnetization of these domains is always perpendicular to the line between the holes which the domains connect. A larger domain occupies the region between the holes and has magnetization which points diagonally along the hole array.

5.2.2 Hysteresis Loop Simulation

Magnetic hysteresis loops can be simulated in OOMMF. To do so, a large field is first applied along a given direction to saturate the sample. The simulation then runs until the total torque is less than a user defined value. The field is then stepped down and the process repeated. By sweeping the field, the M-H loop is simulated and data can be compared to experimental results.
Hysteresis loop simulations were done for a 3 x 4 µm sample. Since generating each loop requires a great deal of computing power and time, only three data points were taken. These points correspond to the three easy and hard axes in the sample and are shown in Figure 5.13.

**Figure 5.13** Simulated hysteresis loops for the 3 x 4 µm antidot sample. The loops were made using OOMMF and then plotted in Excel™. The magnetization of the sample is measured along the field direction.
The remnant percentages for the three simulations as well as the experimental values are given in Table 5.1. The experimental data was taken at 55° while the simulation was run at 53°. Both the experimental and simulated data have their lowest remnant percentages at 0°, medium values at 90°, and highest values along the diagonal direction. Although the absolute percentages are not in good agreement, the data confirms the locations of the easy and hard axes in the samples.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Simulation Remnance</th>
<th>Experimental Remnance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>70.8 %</td>
<td>66.4 %</td>
</tr>
<tr>
<td>53°</td>
<td>86.7 %</td>
<td>X</td>
</tr>
<tr>
<td>55°</td>
<td>X</td>
<td>91.7 %</td>
</tr>
<tr>
<td>90°</td>
<td>77.7 %</td>
<td>87 %</td>
</tr>
</tbody>
</table>

Table 5.1 Remnant percentages for the 3 x 4 μm antidot array from the OOMMF simulations and the experimental MOKE data. The results confirm the directions of the easy and hard axes, though the percentages are somewhat different. The 53° simulated hysteresis loop also provided one more interesting piece of information. To generate this loop, both x- and y-axis loops were taken and subsequently recombined to form the image in Figure 5.11. These loops are shown separately in Figure 5.14. The data is distinctly different along each direction. The x-axis loop shows a sudden change in magnetization, while the y-axis indicates a more gradual transition. We can thus conclude that two different magnetization reversal processes are taking place within the domains along these axes in the same sample. This information would be impossible to determine from our MOKE results, though it may be obtained from V-MOKE.
Figure 5.14 Separate hysteresis loops for the x- and y-axes from the 53° hysteresis loop simulation for the 3 x 4 µm antidot sample. The x-axis loop shows a sudden magnetization reversal, while the y-axis is much more gradual. This indicates that more than one magnetization reversal process is occurring in the sample.

6 Summary and Conclusions

This thesis has shown a study of the in-plane anisotropy of permalloy antidot arrays. We conclude that the type of anisotropy present in the sample is completely dependant on the hole pattern and is unaffected by the anisotropy of the sample before the antidots were added.

The domain structure in the samples has been shown to be affected by the antidot pattern. In the sheet film, large domains are assumed to exist, though they weren’t observed. The antidot samples show very clear domain structure, with small individual domains beginning and terminating at the holes. The hole pattern thus determines the direction and orientation of the domain structure.

Computer simulations, using OOMMF, have been shown that verify the experimental results. These simulations also showed details not seen in the experimental results.
Moreover, the simulations show that it should be possible to design novel materials and determine their properties before actually making the material. This could save significant development time and costs.
7 Suggestions for Further Investigation

7.1 Experimental Techniques

7.1.1 Diffracted Magneto-Optical Kerr Effect

When a laser is incident on either a dot or an antidot array, diffracted beams will be given off. Grimsditch et al.\textsuperscript{17}, working with submicron permalloy dot arrays, used a technique called diffracted magneto-optical Kerr effect (DMOKE) to study their samples. Here, rather than examine the beam reflected from the sample surface, the diffracted beam is examined using standard MOKE techniques. This can provide information about the samples which cannot be determined from conventional MOKE results. DMOKE data may provide insight into what is happening to the magnetization at the hole edges in our antidot samples.

7.1.2 Coercive Field Study

Kersten impurity center theory predicts a definite correlation between the coercive field and the hole pattern\textsuperscript{4} of the antidots, though it was not able to be shown with the data here. More precise measurements of the external field as well as longer sweep times on the MOKE may provide better data to test this theory. Also, this theory should explain the increase in the coercive field between the sheet film and the antidot samples.
7.2 Antidot Samples

This thesis has concentrated on studying the properties of rectangular and square antidot arrays, with the exception of one hexagonal sample. This was done both to collaborate with other ongoing research in our lab, and to simplify the data analysis by using hole patterns with simple symmetries. Other samples are available which have different antidot hole patterns such as diamond shaped arrays. These should be studied in the future to determine if they have useful magnetic properties.

Since the storage potential of these materials is dependant on the hole spacing, it would be of interest to see how small of a spacing could be achieved while maintaining a region of well defined remnance between the holes. Photolithography has a limited resolution which places a lower limit on the hole size, though different techniques such as nanoimprint, or electron-beam, lithoghaphy could be used to produce smaller antidot arrays.

Grimsditch et al.\textsuperscript{18}, working with elliptical dot samples, showed that the main source of anisotropy in the samples was shape anisotropy induced by the ellipticity of the dots. They concluded that it might be possible to create a sample with custom tailored magnetic properties by varying the dot spacings and shapes. It is very possible that the shape of the antidot holes in our samples may have a similar effect on their anisotropy. It would be of interest to create new samples with different hole shapes to see how this affects their properties.
8.1 Appendix 1. LabVIEW™ screenshot from the MOKE.
8.2 Appendix 2. MOKE data from each sample tested.

This appendix contains complete MOKE data for all seven samples which were tested as well as data for the sheet film. For each sample, hysteresis loops along each hard and easy axis, a graph of the in-plane remnance, and a polar plot of the remnant percentage are shown. The data was repeated twice to generate the polar plots, since only 180° of data was taken for any particular sample.
Sheet Film Data

0 Degree Hysteresis Loop

30 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance
3 x 3 µm Array Data

0 Degree Hysteresis Loop

45 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance

<table>
<thead>
<tr>
<th>Angle (deg)</th>
<th>Percent Remnance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>95</td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>200</td>
<td>65</td>
</tr>
</tbody>
</table>

Field (Oe)

M/Msat
4 x 4 Array Data

0 Degree Hysteresis Loop

45 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance
5 x 5 Array Data

0 Degree Hysteresis Loop

45 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance
3 x 4 Array Data

0 Degree Hysteresis Loop

55 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance
3 x 5 Array Data

0 Degree Hysteresis Loop

60 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance

-200 -100 0 100 200
Field (Oe)

-200 -100 0 100 200
Field (Oe)

-100 -50 0 50 100
Field (Oe)

0 50 100 150 200
Angle (deg)

60 65 70 75 80 85 90 95 100
Percent Remnance

0 50 100 150 200
Angle (deg)
3 x 7 Array Data

0 Degree Hysteresis Loop

70 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance
3 µm Hexagonal Data

0 Degree Hysteresis Loop

60 Degree Hysteresis Loop

90 Degree Hysteresis Loop

In-Plane Remnance

Percent Remnance vs Angle (deg)
References

1. R.Compton, M.S. Thesis – Ferromagnetic Resonance Study of the Magnetic Anisotropy of a Bilayer of Fe on FePt, Miami University (2001)