ABSTRACT

INVESTIGATION OF THE MAGNETOSTATICS OF EXCHANGE-COUPLED NANO-DOTS USING THE MAGNETO-OPTIC KERR EFFECT TECHNIQUE

by Sarah C. Hernandez

The effect of inter-dot exchange coupling on the magnetization reversal processes in nano-dots has been investigated on Permalloy dot arrays with dot diameters of 300 nm and thickness of 40 nm. The dots are exchange coupled via 50 nm long Permalloy bridges of width ranging from zero to 60 nm. Chains of five co-linear coupled dots form the unit cell of the array structure. Magneto-optical Kerr effect hysteresis loops are reported with comparison to simulations. With field applied along the coupling direction, nucleation is suppressed by the interdot exchange coupling resulting in highly correlated magnetization patterns. When the field is applied perpendicular-to-the-coupling direction, the exchange interaction has little effect and magnetic reversal is almost identical to arrays of isolated dots. As a result of rotating the applied magnetic field relative to the sample’s coupling direction, unusual hysteresis loops were observed, which could be explained by a combination of the x and y-component of the magnetization.
Investigation of Magnetostatics of Exchange-Coupled Nano-dots using the Magneto-optic Kerr Effect Technique

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This work is dedicated
to my beautiful daughter,

Celeste,

whose angelic smile and laughter

brightens up my day

after a long day of research.
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1 Introduction

1.1 Motivation

Magnetism is seen and felt every day, from the Earth’s own magnetic field to the storage device of personal computers. Therefore scientist and engineers have learn to appreciate this fundamental phenomena that has shaped our present technology. The Nobel prize granted in Physics in 2007 to Albert Fert and Peter Grunberg for the discovery of giant magnetoresistance (GMR) gave rise to miniature hard disk drives, that contained increasing higher memory storage, are now used in every day computers, laptops, and even music players. Combining the nano-world and magnetism has shown great promise to relevant applications, especially from magnetic nano-dot arrays. Magnetic nano-dot array studies\textsuperscript{1,2} have shown that these structures could be use for magnetic random access memory, magnetic recording media, and magnetic sensors. Intensive studies\textsuperscript{3,4} investigate the magnetostatics of the nano-system by magnetization reversal, which provides knowledge of the fundamental properties of the magnetic material.

1.2 Purpose

Past studies have investigated various isolated dots that are dependent on size, shape, and inter-dot spacing on the magnetization reversal.\textsuperscript{5,6,7} Novosad \textit{et. al.}\textsuperscript{7} have investigated the inter-dot interaction via dipolar coupling in nano-dots and concluded that the ratio $d/R$, where $d$ is the distance between dots and $R$ is the radius of the dots, is the main cause in manipulating when the formation of a vortex occurs, also known as the nucleation fields, in the nano-dots. This work

and also of Zhu et al.\textsuperscript{8} have shown that vortex nucleation in dipole-coupled dots begins in the most outer dots in an array and moves inward towards the most center dots in the array, while annihilation of the vortex occurs from the center dots in the array to the outer dots. Barpanda et al.\textsuperscript{9} have simulated the evolution and propagation of magnetic vortices in exchange coupled nano-spheres and calculated that the coupling strength would affect the vortex curling configuration and annihilation fields. In this thesis, we investigate the effects of exchange coupling arrays of nano-dots, by inducing the exchange energy via bridging the dots in elements of 5 nano-dot chains. We will observe the vortex magnetostatics by using the longitudinal magneto-optic Kerr effect (MOKE) technique by applying the field along and perpendicular to the coupling direction. We will then obtain information of the shape anisotropy of the system by applying the field at oblique angles to the sample. We hope to further contribute to the fundamental understanding of the magnetization reversal in exchange coupled nano-dots.


2 Background Theory

2.1 Magnetic Energies

Magnetization reversal is as follows: by applying a magnetic field, the magnetic moment in a material will tend to align itself along that field, but if we apply the magnetic field in the opposite direction then the magnetic moment will reverse from one direction to the opposite direction, 180° rotation. What determines this reversal process is the delicate balance between the Zeeman, exchange, magnetostatic and magnetic anisotropy energies. Each energy constitutes their own effect on the magnetic moments. For instance, the Zeeman energy is the interaction of the magnetic moments with the applied magnetic field, $H_{\text{applied}}$. The Zeeman energy is defined as

$$U_{\text{Zeeman}} = -\mu \cdot \vec{H},$$

where $\mu$ the atomic magnetic moment in the material in units of ergs/Oe, $H$ is the applied magnetic field in units of Oe, and the Zeeman energy is defined in units of ergs.

2.1.1 Exchange Energy

The exchange energy plays a very important role in magnetic materials. In such a material, the atoms will exchange their outer electrons with one another; therefore we observe an overlap in the wave function. This is known as direct exchange. In Figure 2.1, we see an electron 1 orbiting proton 1 and electron 2 orbiting proton 2 [Fig. 2.1(a)], but since electrons are indistinguishable we can also consider the case of electron 1 orbiting proton 2 and electron 2 orbiting proton 1 [Fig. 2.1(b)].

![Figure 2.1: Two atoms adjacent to each other, (a) and (b) show two different orbiting situations.](image)
The exchange force is dominated by the Pauli Exclusion Principle and Heisenberg was able to show that the exchange energy plays an important role in ferromagnetism. The exchange energy equation is

\[ E_{\text{ex}} = -2J_{\text{ex}} S_i \cdot S_j, \]  

where \( S_i \) and \( S_j \) are the angular momenta of the electrons and \( J_{\text{ex}} \) is the exchange integral. If \( J_{\text{ex}} \) is positive then the exchange energy is at a minimum magnitude when the spins are parallel and at a maximum magnitude when the spins are anti-parallel. If \( J_{\text{ex}} \) is negative, then the lowest energy allowed is when the spins are anti-parallel to each other. Therefore in a ferromagnet, \( J_{\text{ex}} \) must be positive (Fig. 2.2). The latter case describes interaction within an antiferromagnet, which is beyond the scope of this work.

![Figure 2.2: Schematic drawing of alignment of spins in a ferromagnet and antiferromagnet.](image)

Ferromagnetic domains are small regions within a magnetic material, where the magnetic moments are aligned in some kind of configuration to each other to minimize dipole energy. Dipolar energy, also known as the magnetostatic energy, is the prime motivation in domain formation. The region that is located between domains, known as domain walls, is regions where the exchange energy is high.

### 2.1.2 Domain Formation

Domain formation occurs through the process of minimizing the magnetostatic energy, such that the state of the magnetic material is overall in a minimum energy state. If we imagine a magnetized block that has a single domain, with north and south poles present, the internal field
field lines present inside the block) wants to magnetize the block in the opposite direction [Fig. 2.3(a)]. This internal field is known as the demagnetizing field, $H_d$. By dividing the block into domains, the induced demagnetizing field will create a domain pattern that will have minimum magnetostatic energy, therefore demagnetizing the material [Fig. 2.3(b) and 2.3(c)].

![Figure 2.3](image)

Figure 2.3: Schematic of the magnetostatic energy being reduced by domain formation. (b) and (c) are known to have uniaxial or two-fold anisotropy and crystal cubic or four-fold anisotropy, respectively. From Reference 10.

Looking more closely at Figure 2.3(b) and the definition of minimum overall energy, the two domain moments are not able to align parallel at the domain wall, therefore the exchange energy will increase, but there is still less dipole energy than Figure 2.3(a). Figure 2.3(b) demonstrates an example of uniaxial or two-fold anisotropy. Figure 2.3(c) is an example of a closure domain, i.e. north and south poles are not present in the material, thus there is no dipole energy and the overall energy is at a minimum. This is observed in a crystal with cubic or four-fold anisotropy.

By applying this basic principle in a ferromagnetic nano-dot, a vortex domain will form. In Figure 2.4(a), all moments are parallel to one another when the applied field is present, thus the exchange energy is at minimum, but maximum magnetostatic energy. Figure 2.4(a) illustrates the point of saturation, $M_s$. When the applied field is taken off the material, $H_{applied} = 0$, the vortex domain will form, such that there is increase in the exchange energy and a decrease in the magnetostatic energy, resulting in the nano-dot becoming demagnetized.

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By understanding how the exchange energy and magnetostatic energies interact inside a magnetic material, we are able to understand domain formation along with the magnetization reversal that is shown in a hysteresis loop.

### 2.2 Magnetization Reversal

By applying a field, a ferromagnetic material will experience magnetization reversal, which is shown by a hysteresis loop (Fig. 2.5).

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12 Carl R. Nave, *HyperPhysics: Hysteresis Loops*, Department of Physics and Astronomy, Georgia State University, (2006) [http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html](http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html)
Figure 2.5(a) shows the initial state of the moments and domains in a polycrystalline magnetic material. Starting from zero field, the magnetization curves show a non-linear behavior when a field is applied. When the material reaches saturation at a high applied field, the domain moments are aligned in the direction of the applied field [Fig. 2.5(b)]. At remanence (zero field applied) the magnetization is less in magnitude than at saturation—this is known as the remanence magnetization. The amount of applied field required to reach zero magnetization after coming from saturation is also known as the coercive field [Fig. 2.5(c)]. At the coercive field, $H_c$, the domain moments will construct a pattern that demagnetizes the material, as discussed above. In Figure 2.5(d), the material will reach saturation in the opposite applied field direction, then the domain moments will be in the opposite direction from the saturation shown in Figure 2.5(b).

A hysteresis loop provides a lot of information about the magnetic properties of the material. For example, coercivity, $H_c$, the width of the hysteresis loop can identify whether the material is a magnetically “soft” or “hard”—magnetically hard if $H_c$ is large, and magnetically soft if $H_c$ is small. More about this concept will be discussed later in the context of magnetic vortices.

2.3 Magnetic Anisotropy

2.3.1 Magnetocrystalline Anisotropy

The primary source for the magnetocrystalline anisotropy energy is the spin-orbit interaction. The spin-orbit interaction is from the electron’s spin interaction with the magnetic field from its own orbital motion. For instance, when an applied magnetic field is present, it will try to reorient the electron’s spin, thus reorienting the electron’s orbit, but the electron’s orbit is strongly coupled to the atomic lattice, therefore the electron will resist rotating the spin axis. Compared to the orbit-lattice coupling, the spin-orbit coupling is weak, where only a few hundred oersteds can be applied and overcome the spin-orbit coupling (Fig. 2.6). The energy that is required to overcome the spin-orbit coupling is known as the magnetocrystalline anisotropy.
The magnetocrystalline anisotropy energy is not only the energy to overcome the spin-orbit coupling, but is also known as the amount of energy needed to align the moments in the preferred crystallographic direction, known as the easy axis (Fig. 2.7). Applying a field along the easy axis, saturation can be achieved at very low fields, whereas in order to get the same results when the field is applied along the hard axis, a high field must be applied.

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Figure 2.6: Summary of spin-orbit-lattice interactions. From Reference 13.

Figure 2.7: A body-centered cubic iron unit cell that shows the easy, medium, and hard axis. The axis a, b, and c represent the x-y-z plane in the unit cell. Modify from Reference 10.

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From knowing the easy and hard axis of a material, we can conclude that when the magnetization points along the hard axis, the crystal has a higher energy than when it is oriented along the easy axis. The magnetocrystalline cubic anisotropy energy density is describe by

\[ E = K_0 + K_1 (\alpha_1^2 \alpha_2^2 \alpha_3^2 \alpha_4^2 \alpha_5^2 \alpha_6^2) + K_2 (\alpha_1^2 \alpha_2^2 \alpha_3^2) + \cdots , \]

(2.2)

where \( K \) represents the anisotropy energy densities in units of ergs/cm\(^3\) and \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) represent the direction cosines the magnetization makes with axis \( a, b, \) and \( c, \) respectively (Fig. 2.7). The area difference between the easy and hard axis curves in Figure 2.8 is the measurement of the magnetocrystalline anisotropy energy in a single crystal. For example, by applying a magnetic field along a material’s hard axis, we can change the direction of the magnetic moments from the easy axis to the hard axis. The energy that is needed to rotate the magnetization from the easy axis to the hard axis is the same amount of energy needed to overcome the spin-orbit coupling that is present in the material.

![Figure 2.8: Magnetization curves and unit cells for iron (a) and nickel (b). From Reference 13.](image)

By applying a field along the easy axis we can observe domain wall motion. In Figure 2.9(a), a single-crystal disk of iron is demagnetized, \( M_s = 0, \) along four of the six possible easy
directions, [010], [100], [0\bar{1}0], and [\bar{1}00]. If a field is applied in the [010] direction, we observe domain wall motion, as the domain that has its moment pointing in the [010] pushes the other domains out, therefore the magnetization becomes greater than zero [Fig. 2.9(b)]. Finally the unfavorable domains are removed and saturation is achieved [Fig. 2.9(c)]. If we were to apply a magnetic field 45° from the easy direction, [110], we see domain wall motion followed by coherent rotation (Fig. 2.10). Starting from a demagnetized state [Fig. 2.10(a)], the domains that are approximately in the same direction as the applied field are more favorable, therefore eliminating the less favorable domains [Fig. 2.10(b)]. Eventually there are only two domains that will exist [Fig. 2.10(c)], but to reach total saturation, the domain moment vector will rotate to the direction of the applied field [Fig. 2.10(d)]. Domain rotation only occurs at very high fields since it has to overcome the crystal anisotropy energy.

Figure 2.9: Schematic of domain wall motion in a single crystal iron disc, when the field is applied along the [010] direction. From Reference 13.
Some crystals have a uniaxial anisotropy. In a uniaxial crystal, the easy direction is preferably in one directional axis, for instance the $c$ axis in hexagonal close packed crystals. Then equation 2.2 becomes

\[ E = K_0 + K_1 \cos^2 \theta + K_2 \cos^4 \theta, \]  

(2.3)

where $\theta$ is the angle between the magnetization and the $c$ axis. If $K_1$ and $K_2$ are both positive, then $E$ is at a minimum when $\theta = 0^\circ$. Therefore at the $c$ axis, it becomes the easy direction, where the magnetization can point either parallel or antiparallel to it. A uniaxial crystal will favor stripe domain formation (Fig. 2.11). If $K_1$ and $K_2$ are both negative, then the minimum occurs at $\theta = 90^\circ$, wherein the easy plane of magnetization will be perpendicular to the $c$ axis. Crystal field anisotropy will not play a major role in our system, due to the low crystal field and polycrystalline nature of our samples.

Figure 2.11: Stripe domain structure of a uniaxial crystal. From Reference 13.
2.3.2 Shape Anisotropy

Shape anisotropy is determined by the diameter and thickness of the material. A simple case is a sphere, then there is no preferred orientation for the moments; therefore, there is no overall shape anisotropy. Considering a magnetic material that is not spherical, the material’s easy axis is along the semi-major axis (Fig 2.12).

![Figure 2.12: An ellipsoid with semi-major axis c and semi-minor axis a, with a magnetization pointed θ from the semi-major axis. From Reference 13.](image)

To better understand shape anisotropy we must look at the magnetostatic energy,

$$E_{ms} = \frac{1}{2} \vec{H}_d \cdot \vec{M}. \quad (2.4)$$

The demagnetizing field is proportional to the size of the magnetization:

$$\vec{H}_d = N_d \vec{M}, \quad (2.5)$$

where $N_d$ is called the demagnetizing factor and depends on the shape of the material. In the ellipsoid (Fig. 2.12), the semi-major and semi-minor will have different demagnetizing factors, $N_c$ and $N_a$ respectively. In the case of the ellipsoid, the magnetostatic energy will become

$$E_{ms} = \frac{1}{2} M^2 N_c \frac{1}{2} (N_a + N_c) M^2 \sin^2 \theta, \quad (2.5)$$

when the magnetization is at an angle $\theta$ to the semi-major axis. When $\theta = 90^\circ$, the magnetostatic energy becomes greater than when $\theta = 0^\circ$, therefore, we can conclude that the semi-major axis is the easy axis, while the semi-minor axis is the hard axis. The shape anisotropy constant is

$$K_s = \frac{1}{2} (N_a - N_c) M^2; \quad (2.6)$$

therefore in the case of a sphere, $N_a = N_c$, then $K_s = 0$, then the shape anisotropy disappears.
In the case for a thin film disk, the finite aspect ratio is determined by the thickness and diameter of the disc of the material. In a disk with thickness much smaller than the radius, the hard axis is normal to the film, which is known as easy plane uniaxial anisotropy (Fig. 2.13). This terminology is used because the disk has infinite amount of easy directions along the plane, therefore the uniaxial nature becomes the hard axis, which is out of the plane of the disk. We can induce in-plane anisotropy by manipulating the shape of this thin film disk.

![Figure 2.13: A thin film disk with radius R and thickness L.](image)

Although magnetocrystalline anisotropy will not affect our system, the shape anisotropy will affect our system, especially in the coupled nano-dots. We will expect that the uncoupled nano-dots, i.e. square array of single dots, will have a four-fold anisotropy, because of the symmetry of the array. The coupled nano-dots are expected to have a two-fold anisotropy, due to the bridge coupling between the 5 dots in a linear chain. Given shape anisotropy, the easy direction will be along the coupling direction, therefore providing a uniaxial nature to the system (Fig. 2.14).

![Figure 2.14: (a) shows an array of uncoupled nano-dots with four-fold anisotropy. (b) shows an array of coupled nano-dots with two-fold anisotropy.](image)
2.4 Magnetic Vortices

As discussed earlier, a vortex is a special curling magnetic configuration, where the center moment is pointing up or down and the chirality is either counterclockwise or clockwise (Fig. 2.15). As noted in Figure 2.16, when a nanodot is saturated, the magnetostatic energy is at a maximum value and the exchange energy is at a minimum value. When the magnetic field applied is zero, the magnetostatic energy will be minimized through domain formation; therefore, when coming from saturation, the exchange energy increases as the magnetostatic energy decreases and the only domain that allows zero moment remanence in a low anisotropy nano-dot is a vortex domain. Later discussions will show that vortex formation will depend on several parameters.

Figure 2.15: Different examples of vortices, cylindrical (a), rectangular (b), elliptical (c), multilayered (d), and ring shaped (e). In (f) classical multi-domains are shown for larger elements where the anisotropy is dominant. From Reference 14.

A vortex domain has a signature hysteresis loop that describes the movement of the vortex inside the nano-dot. For instance, if we observe a simple submicron Permalloy nano-dot, starting from saturation, Figure 2.17(a), we see that the arrows are aligned along the applied field. Coming down from saturation while approaching remanence, we get nucleation of the vortex domain in the disk [Fig. 2.17(b)]. From nucleation to the remanent state, the vortex becomes centered in the nano-dot. At remanence, the nano-dot is completely demagnetized, therefore in the vortex state [Fig. 2.17(c)]. After remanence, when the applied field is in the opposite direction, we see annihilation of the vortex domain, which involves moving the vortex out of the dot. As discussed above in Figure 2.9 and Figure 2.10, the vortex is pushed towards the left of the nano-dot since the magnetic moments already in the direction of the applied field become more favorable than the moments opposing the applied field [Fig. 2.17(d)]. Annihilation of the vortex happens at higher magnetic fields than the nucleation of the vortex. Following annihilation the nano-dot will be in saturation [Fig. 2.17(e)] in the opposite direction from Figure 2.17(a).
The vortex domain is dependent on the finite-ratio aspect and one seminal study done by Cowburn et. al.\textsuperscript{5} showed a size dependence on the formation of the vortex phase versus the single-domain phase (Fig. 2.18 and Fig. 2.19). They concluded that with increasing thickness and diameter, the vortex is favored over a single-domain phase and the vortex state annihilates at higher fields.

Figure 2.17: Simulated hysteresis loop for submicron nano-dot, which corresponding snapshots. From Reference 2.
Figure 2.18: For each loop the horizontal axis is the applied field and the vertical axis is the magnetization. The vortex phase formed at higher diameters and thickness. From Reference 5.

Figure 2.19: In the graph above, ● = single domain and ○ = vortex. The graph shows that with increasing diameter and increasing thickness a vortex phase will form. From Reference 5.
3 Sample Preparation

3.1 Bulk Permalloy

A special alloy that is used for studying nanodots is Permalloy (NiFe). Permalloy is an iron-nickel alloy that contains 50% to 80% nickel. This material is ferromagnetic and has a very high permeability at low applied fields, which implies a high susceptibility. Permalloy is face-centered cubic and has uniaxial cubic anisotropy, with the easy axis in the <100> direction. Permalloy is a soft magnetic material with $H_c = 1$ Oe in the easy direction and in the hard direction, $H_A = 3$ Oe. In this work, we will focus on Permalloy nano-dot array thin films, which is 80% nickel and obtain great insight into the investigation of the vortex magnetostatics in Permalloy nano-dots.

3.2 Exchange-coupled nano-dot sample

We investigated five Permalloy dot array samples with various bridge widths and a bridge length of 50 nm, which were fabricated by electron-beam lithography and supplied by Hitachi Global Storage Technologies. The array dimensions are 1.925 mm x 1.925 mm. Each nano-dot has a diameter of 300 nm, thickness of 40 nm, and separated by 50 nm in the non-connecting bridge direction. Four samples will consist of a 5 dot coupled chain array with 0 nm (no bridge), 20 nm, 40 nm, and 60 nm bridge width. The last sample is a 2 dot coupled chain array with a 40 nm bridge width. All scanning electron microscopy images were provided by Hitachi. (Fig. 3.1, Fig. 3.2, Fig. 3.3, and Fig. 3.4) The samples were separated by using a diamond scribe. It was very difficult procedure to separate the samples, since the samples were only separated by a 2 mm on a silicon substrate. Much preparation, care, and practice was performed before even cutting the delicate sample. A hysteresis loop taken by a vibrating sample magnetometer (VSM) is provided from the continuous NiFe film manufactured by Hitachi (Fig. 3.5). Unfortunately this technique will not be used for the coupled nano-dots, because there is too much noise in the VSM signal due to not enough material. The narrow loop and low coercivity shown in Figure 3.5 indicates the high quality of the film.
Figure 3.1: SEM image of 5 dot chain coupled with 20 nm bridge width. Top image is zoomed out and bottom image is zoomed in.
Figure 3.2: SEM image of 5 dot chain coupled with 40 nm bridge width. Top image is zoomed out and bottom image is zoomed in.
Figure 3.3: SEM image of 5 dot chain coupled with 60 nm bridge width. Top image is zoomed out and bottom image is zoomed in.
Figure 3.4: Zoomed out SEM image of 2 dot chain coupled with 40 nm bridge width.

Figure 3.5: VSM hysteresis loop of NiFe continuous film manufactured by Hitachi.
4 Experimental Technique

4.1 Theory of The Longitudinal Kerr Effect

Magneto-optic effects were discovered by Michael Faraday\textsuperscript{15} in 1846, which he described the magnetically induced rotation of the plane of polarization of light propagating through glass. It would be some time, before John C. Kerr\textsuperscript{15} would announce his discovery of the polar Kerr effect in 1876, which described how the reflected polarized beam intensity from a pole piece of an iron fluctuated by reversing an applied field. Kerr concluded that this phenomenon described a magnetic rotation of the plane of polarization, but did not realize that the ellipticity was also affected.

4.1.1 Types of Kerr effects

Today, we know of three basic Kerr effects, polar, longitudinal, and transverse Kerr effect (Fig. 4.1). Transverse Kerr effect involves applying the magnetic field parallel to the surface and normal to the plane of incidence. While the intensity of the s-polarization $I_s$ remains unchanged, the p-polarization $I_p$ is increased or decreased slightly by magnetization reversal. There is change in the rotation and ellipticity of the reflected beam, which will include components present in the s and p planes.

![Figure 4.1: Different types of MOKE. From Reference 16.](image)

Polar Kerr effect is when the magnetization of the sample is normal to its surface and produces the largest polarization change. During polar Kerr effect, when it undergoes magnetization reversal, the reflected beam becomes an ellipse that has been rotated slightly away

\textsuperscript{15} C. C. Robinson, “The Longitudinal Kerr Magneto-Optic Effect,” MS Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, Boston, Massachusetts (1960)

from the plane of incidence and the direction of the rotation and sign of ellipticity is reverse. In the longitudinal Kerr effect, the magnetic field is applied parallel to the surface and along the plane of incidence. Like the polar effect, the reflected beam is a rotated ellipse for an incident s or p-radiation and is roughly 1/3 to 1/4 polarization change produced by the polar effect. For our purposes we will focus on the longitudinal magneto-optic Kerr effect (MOKE).

4.1.2 Physical Approach to Longitudinal MOKE

In Robinson’s thesis,\textsuperscript{15} he provided a very simple explanation of the physical interactions in the longitudinal MOKE. In Figure 4.2, a magnetic sample is shown with an s-polarization incident on the sample and the magnetization $M$ of the sample is along the p-plane. When the incident light hits the magnetic material, a current, $J$, is induced by the incident electric field, $I_s$. $J$ is perpendicular to $M$ and $J$ will induce a Lorentz force, which will be exerted on the moving electrons. The displacement of the electrons induces a Hall effect to appear normal to the plane of $J$ and $M$. This is shown in Figure 4.2 as $E_k$ and is also known as the Kerr component. The Kerr component gives rise to a reflection component in the p-plane $R_p$ along with the metallic reflection, $R_s$. The $R_s$ and $R_p$ components will provide the characteristic elliptic polarization through vector addition. When reversing the magnetization in the sample this will reverse the Kerr component, therefore the elliptical polarization is rotated about the s-plane. This illustration is similar when the incident light is in the p-plane.

![Figure 4.2: A simple explanation for the longitudinal MOKE. From Reference 15.](image)
4.1.3 Mathematical Approach to the Longitudinal MOKE

The Kerr effect is also related to the spin-orbit interaction, which will be explained below, but the polarization change is due to the difference between the Fresnel reflection coefficients for right and left circularly polarized light. In this thesis, I will briefly summarize this difference, while a complete derivation may be found in Reference 17.

Since we already know that a current is induced from the incident light hitting the magnetic material, Reference 17 explains that the total current density is described by

\[ J = J_0 + J_1, \]  

(4.1)

where

\[ J_0 = \sigma_0 \cdot E + \alpha_0 \cdot (\partial E/\partial t), \]  

(4.2)

\[ J_1 = \sigma_1 \cdot E + \alpha_1 \cdot (\partial E/\partial t), \]  

(4.3)

where \( \alpha_0 \) and \( \alpha_1 \) are the components for the polarizability tensor, \( E \) is the electric field and \( \sigma_0 \) and \( \sigma_1 \) are components to the conductivity tensor. As quoted from Reference 17, “\( J_0 \) is the induced current density in the absence of any spin-orbit interaction [and] \( J_1 \) arises from spin-orbit interaction; only the magnetic electrons contribute to \( J_1 \), and this points out the connection of the magnetic and optical properties of metals in so far as the spin-orbit interaction is responsible for it.” Now the polarization rotation, \( \Phi \), due to the Kerr effect can be described by

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

(4.4)

and has a corresponding ellicipity, \( E \),

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

(4.5)

where \( N_+ \) and \( N_- \) are the components for the complex index of refraction of a ferromagnetic material and are given by

\[ N_- = \sqrt{1 + 4\pi \left( \frac{\alpha_0}{\omega} + \frac{\sigma_0}{\omega} \right) + i4\pi \left( \frac{\alpha_1}{\omega} + \frac{\sigma_1}{\omega} \right)}, \]  

(4.6)

\[ N_+ = \sqrt{1 + 4\pi (\alpha_0 + \frac{\sigma_0}{i\omega}) - i4\pi (\alpha_1 + \frac{\sigma_1}{i\omega})}, \] (4.7)

where \( \omega \) is the frequency of the light from the laser. All of these values are constants, therefore Equation 4.4 and 4.5 may be reduced to

\[
\frac{N_+ - N_-}{N_+ N_- - 1} = (-4\pi) \frac{(\frac{\sigma_1}{i\omega}) + i\alpha_1}{(n-ik)[(n-ik)^2-1]},
\] (4.8)

where \( n \) is the real component and \( k \) is the imaginary component of the index of refraction.

Since \( J \) only arises from the spin-orbit interaction, the magnetic signal only depends on \( \sigma_1 \) and \( \alpha_1 \). Reference 17 equations (48) and (49) show that \( \sigma_1 \) and \( \alpha_1 \) are proportional to the magnetization of a sample; therefore we can conclude that the Kerr rotation and ellipticity of a magnetic sample is directly proportional to the magnetization of the sample, which can be used to obtain the magnetization reversal of a magnetic material.

**4.2 Experimental Setup**

Figure 4.3 describes the MOKE setup used in the lab. By shining a polarized 632.8 nm HeNe laser at an angle of incidence 15° to the plane of the thin film and applying a magnetic field along the plane of the film, as described above the magnetic moment will change the polarization and reflectivity of the incidence light, which is then analyzed by an analyzer and a photodiode will detect the signal. A photoelastic modulator (PEM) was used to enable lock-in detection to improve signal to noise ratio. A computer program, LabView, will record the intensity of the light versus the applied magnetic field, and control the Gauss meter, Hall probe, and lock-in amplifier via GPIB connections. The laser used in this experiment is a Spectra-Physics model 117A. Specifications for the laser are provided in Appendix A.
In the first part of the experiment the PEM was placed before the laser as seen in Figure 4.3. The first part will involve observing magnetization reversal along and perpendicular to the coupling direction for all the samples. In the second part, the PEM was placed before the analyzer and a new sample holder device was built to provide more degrees of freedom and better control. This new system includes a ½” xyz translation stage, a 1” optical diameter center mount, a 1” diameter rotation stage and two stackable lens tube at 2” and 3” tube depth (Fig. 4.4 and Fig. 4.5). The x-y-z translation stage provides movement of the sample in the xyz plane, while the center mount controls the tilt of the sample, and the rotation stage gives the capability to rotate the sample. The stackable tubes provide for the sample to be placed on a light holder that will not give much load to the center mount. Screwed into the end of the stackable tubes is a machined aluminum rod that has a grid etched at the end of the rod. Since the sample holder is more precise, this provides finer rotation angles for the sample between 0° to 90° from the applied magnetic field.

Before aligning the sample, the PEM, analyzer, and photodiode were placed parallel to each other and the center of each instrument were at the same height. The alignment procedure involves placing the sample on the grid that was etched at the end of the sample holder, then rotating the sample until the plane of the sample is completely parallel to the magnetic field. The next step is to center the sample precisely in all three directions in the magnet pole pieces. Then
The sample is tilted so the incident light from the laser hits directly on the sample and the reflected light passes through the center of the PEM. Thus the laser scattering plane was parallel to the optical table. The laser polarization vector $I_p$ makes an angle $\beta$ with respect to the incident plane. $\beta$ was typically 90°, but was varied to determine the difference in the magnetization signal from s and p-polarization and 45°, which will be discussed later in Section 6.2.

Figure 4.4: MOKE set-up in the lab with PEM placed in front of the analyzer.
Figure 4.5: Sample holder used for the MOKE. (a) shows the sample holder previously used, (b) and (c) show the new sample holder device at an angle and front view, respectively.

4.3 Micromagnetic Calculations

Experimental results were compared to micromagnetic calculations performed using NIST’s OOMMF code. The program integrates the Landua-Lifshitz equation,

\[
\frac{dM}{dt} = -\gamma M \times H,
\]  

(4.9)

by using an Adams type predictor-corrector method over a user defined time step. Parameters used for the simulation were saturation magnetization \(M_s = 860\ \text{emu/cc}\), exchange constant \(A = 1.3 \times 10^{-6}\ \text{erg/cm}\), and cell size of 5 nm. A mask was used for the unit cell in OOMMF, where the color black represents that the material is fully magnetic (Fig. 4.6). Field parameters were set as 0.3 T – 0.1 T with 20 steps, 0.1 T – -0.1 T with 50 steps, and -0.1 T – -0.3 T with 20 steps. Initial magnetization was set at random. The complete hysteresis loops were simulated for each sample mentioned above and magnetic state “snapshots” were obtained for points of interest along these simulated loops.

Figure 4.6: Mask of unit cell 5 nano-dot chain with 20 nm bridge width.
5 Results I

5.1 Applied Field Along the Coupling Direction

For comparisons, Figure 5.1 shows MOKE hysteresis loops and simulations for the five chain nano-dots with bridge widths of 0, 20, 40 and 60 nm, when the field is applied along the coupling direction or chain length. Fig. 5.2, Fig. 5.3, Fig. 5.4, Fig. 5.5 each show the individual MOKE hysteresis loops and simulations for 0, 20, 40, and 60 nm, respectively. Figure 5.6 shows complete MOKE data for 0, 20, 40, and 60 nm, respectively.

As observed in Figure 5.2, the experimental data for the array of dots with no bridge shows typical vortex behavior, where nucleation occurs at a low positive field when decreasing from saturation with annihilation at approximately -630 Oe. The simulated loop is in qualitative agreement with the experimental data and the magnetic state snapshots related to the simulated loop gives insight into the dipolar interaction between the dots, which is reflected in the lower vortex nucleation and annihilation field regions compared to the coupled nano-dots. These results are consistent with Reference 7. By observing the snapshots, nucleation occurs first in the outer dots followed, within 60 Oe, by the interior dots, which is also consistent with Reference 8 and Reference 18. This is due to the strong dipolar-coupling between the dots. This sequential nucleation is not observed in the MOKE data since the unit cell in not really five dots but rather a single dot. In snapshots that are not shown, one observes a buckling domain in the inner dots at 80 Oe, while a “C” shaped domain forms in the center of the dot at 40 Oe, as has also been observed in Reference 19.

In the samples where the dots are coupled via bridge into five dot chains, exchange coupling introduces two features: suppression of the vortex formation and an addition step in the reversal process that is not seen in the uncoupled dots. Suppression of the vortex formation is shown by an increasing nonzero remanent moment with increasing bridge width. Simulated loops, which consist of an idealized chain, i.e. perfect cylindrical dots with rectangular bridges, indicates that vortices form sequentially from the outer dots to the inner dot. The outer dots form vortices first because the dipolar-coupling from neighboring dots in the non-connecting direction have a

strong interaction between each other. Remanence is shown through the micromagnetic snapshots in Fig. 5.3(b), Fig. 5.4(b), and Fig. 5.5(b), which shows that a nonzero remanence manifests within the inner dots with a large moment in the three inner dots. In Fig. 5.3(b), Fig. 5.4(c), and Fig. 5.5(b) shows the formation of a well-defined “S” shaped domain. The exchange energy is steadily increasing in the interior dots as the system approaches nucleation from the remanent state. While there are no “C” shaped domains observed like in the isolated nano-dots seen in the coupled nano-dots, the “S” shaped domain is associated with the increase in the exchange energy. The additional step seen at fields approximately 65, 62, and 126 Oe in the 20, 40 and 60 nm bridge samples respectively, becomes more pronounced with increasing bridge width. This is related to the suppression of nucleation in the inner dots by the exchange coupling between them. To better understand the energy interactions inside this system, we will focus on the 60 nm bridge data and simulation.

By observing Fig. 5.5 and the associated OOMMF simulation energy terms in Fig. 5.7, approaching from saturation into remanence [snapshot (a)] to just prior to the inner dots nucleating [snapshot (b)], both the Zeeman and dipole (demagnetization) energies remain relatively constant (within 2%), while the exchange energy steadily increase by a factor of 2 (Fig. 5.7). Snapshot (c) and snapshot (d), taken from the same field, but (c) is prior to stabilization of the final magnetic state at that field, indicates the processes of the magnetic moment bridge switch, followed by vortex nucleation in the inner dots. Note in snapshot (c) a temporary appearance of double vortices. This process indicates that the exchange energy builds up through the bridge coupling, which is ultimately released by a switching of the bridge magnetization. This then is followed by vortex nucleation within the inner dots and a decrease in the Zeeman, dipole, and exchange energies.

Discrepancies that are present between the MOKE and OOMMF data, overestimating the vortex nucleation and annihilation fields, are associated with the uncertainty in modeling the precise structural details of the dots and the geometry of the coupling links. These details are crucial to the accurate modeling of the data. We have showed that simulated vortex annihilation fields more closely matches the data if we replace our idealized chain with tapered walls rather than the rectangular walls originally used. Tapered walls would be reasonable since e-beam lithography would likely fabricate the samples with such walls. This was achieved by varying
the thickness of the taper walls by using the gray scale capabilities in OOMMF. We have also shown that the simulated bridge switching field becomes in more agreement with experimental data by varying the bridge thickness, which has the effect of decreasing the exchange coupling the dots. We have also shown that a five dot chain array with four nearest neighbor chains showed negligible improvement in these discrepancies. Therefore, while idealized models give us insight into important details in the data, precise structural details of the system are crucial to accurately model the data. Finally, the random chirality distribution of the end dots in the spin pattern found using OOMMF in Fig. 5.2, Fig. 5.3, Fig. 5.4 and Fig. 5.5 is due to the symmetric geometry of the dots in the chain array relative to the applied field.\textsuperscript{20}

5.2 Applied Field Perpendicular to the Coupling Direction

When the field is applied perpendicular to the coupling direction, results for the coupled nano-dots were similar to the vortex behavior for uncoupled dot arrays (Fig. 5.8). This can be explained by the fact that following from saturation normal to the coupling direction, bistability in the remanent state of the bridges favors simultaneous nucleation in the dots. Similar effects were seen in dipolar coupled dots, where when the field is applied along the chain, dipolar interactions suppressed vortex formation, but this was not seen when the field was applied perpendicular to the chain.\textsuperscript{7} For the sample with bridge width 60 nm, the moment that is present at remanence is associated with the shape anisotropy, because the width of the bridge is now larger than the length of the bridge, so the moment will prefer to stay normal to the coupling direction. Note that the above results have been published in Reference 21.

Figure 5.1: Hysteresis loops by MOKE (open circles) and OOMMF simulations (solid line) for a five dot-coupled chain array unit cell with varying bridge width, (A) 0 nm, (B) 20 nm, (C) 40 nm, and (D) 60 nm. “Snapshots” show magnetic state points from the simulation. From Reference 21.
Figure 5.2: Five dot-chain coupled with 0 nm bridge MOKE data (open circles) and OOMMF simulations (solid line) with magnetic state “snapshots”. From Reference 21.
Figure 5.3: Five dot-chain coupled with 20 nm bridge MOKE data (open circles) and OOMMF simulations (solid line) with magnetic state “snapshots”. From Reference 21.
Figure 5.4: Five dot-chain coupled with 40 nm bridge MOKE data (open circles) and OOMMF simulations (solid line) with magnetic state “snapshots”. From Reference 21.
Figure 5.5: Five dot-chain coupled with 60 nm bridge MOKE data (open circles) and OOMMF simulations (solid line) with magnetic state “snapshots”. From Reference 21.
Figure 5.6: MOKE data for coupled nanodots, when field is applied along the coupling direction.
Figure 5.7: OOMMF energy graphs for 5 chain coupled nano-dot 60nm bridge.
Figure 5.8: MOKE data for coupled nano-dots, when the field is applied perpendicular to the coupling direction.
6 Results II
6.1 Rotation at Oblique Angles

Using the MOKE we wanted to rotate the sample to investigate the in-plane anisotropy we might expect for our samples (Fig. 6.1). As mentioned in Section 2.3.2, we hoped to see for our uncoupled nano-dot sample a four-fold anisotropy and for our coupled nano-dot a two-fold anisotropy. Then we would like to compare our results with results using another technique, ferromagnetic resonance, with data obtained using a 35 GHz cavity. Instead of achieving the expectations we were hoping for, an unexpected surprise awaited for us.

![Figure 6.1: Sketch of array of dots with the applied field at an angle θ to the sample's horizontal axis.](image)

6.1.1 Uncoupled Nano-dot Array Sample

Figure 6.2 shows the hysteresis loops obtained from rotating the sample through 0° to 90° and Figure 6.3 shows the nucleation, annihilation, and remanence data extracted from the loops. Note that 5_0nm stands for 5 chain nano-dot with 0 nm bridge width. This notation will be used in this chapter.

In Figure 6.2, at 0° and 90° we obtain loops as expected from our previous results, but when we rotated the sample between these two angles, unusual hysteresis loops were observed. While 10° and 80° look reasonably as expected, the hysteresis loop seems to begin to rotate phase directions, i.e. saturation begins from the left instead of from the right, between 20° and 70°. Also due to the four-fold symmetry of the nano-dot arrays the loop repeats itself at 30° and 50° and also 20° and 60°. To better understand these loops, a field analysis was completed by finding the nucleation and annihilation fields of the vortex (Fig. 6.3). Since remanence is zero at approximately at all angles, to get the feel for any changes that might happen at low fields, we plotted the slope at zero field, which is also known as the susceptibility $\chi$. The annihilation fields remain relatively constant at $630 \pm 10$ Oe. The nucleation field peaks at approximately $40°$ and
possibly due to inaccurate absolute angle, 40° might be 45°; therefore, the nucleation field data reflects the four-fold symmetry of the nano-dot array. The susceptibility increases between 30° and 50°.

6.1.2 Coupled Nano-dot Array Samples

Figure 6.4 and Figure 6.5 shows the 2_40nm hysteresis loops and field analysis, respectively. Figure 6.6 and Figure 6.7 shows the 5_40nm hysteresis loops and field analysis, respectively. Figure 6.8 and Figure 6.9 shows the 5_60nm hysteresis loops and field analysis respectively. While the 2_40nm, 5_40nm, and 5_60nm displayed similar features, the 5_20nm deviated from this behavior and will be discussed later in this thesis. For all coupled samples we observed what was expected at 0° and 90°, which was discussed in Chapter 5, but at intermediate angles unusual loops similar to the 5_0nm sample were observed.

In the 2_40nm sample, we begin to observe this phase rotation starting at 18° to about 58° (Fig. 6.4). This rotation begins as the lower left lobe slowly rises and the upper right lobe slowly drops. Between 35° and 50° the hysteresis loop seems to stay steady, not much change in the loop’s shape, but shortly after 50° the phase rotation begins but in the opposite direction. It is noted here even at one degree difference the shape of the hysteresis loop can change dramatically and this will become more apparent when there are more nano-dots in the chain with increasing bridge width. The nucleation fields are low at certain angles but peak at higher fields between 10° to 20° and at 58° and 60° (Fig. 6.5). Annihilation fields seem relatively constant until at angles higher than 60°. Remanence is also relatively constant but peaks at 55°. Clearly in this data, the loop structures does not repeat itself up to 90°. In fact measurements to 180° show the existence of a uniaxial symmetry, which was expected of the system.

In the 5_40nm sample (Figure 6.6) we begin to see the phase rotation begin at 30° and ends at around 80°. When compared to the 2_40nm, the 5_40nm begins this phase rotation at a later angle and ends at a later angle. Interestingly at 37° we begin to see the two lobes come together and a decrease in the coercivity, which was seen at 0° to 35°. Eventually the coercivity returns at 42° and later does not disappear again until 75°. This decrease in coercivity is due to the same phenomenon that was discussed in Section 5.2 for when the applied field is 90° to the coupling direction. The hysteresis loop shape does not change much between 0° to 10°, 50° to 60°, and 82° to 90°. The annihilation and nucleation remain constants but increase at around 72°.
(Fig. 6.7). The remanence decreases at 40°, then increases until 68°, followed by a decrease in magnitude. Again measurements on the 5_40nm sample up to 180° indicated the uniaxial symmetry of the sample.

In the 5_60nm sample (Figure 6.8) the phase rotation begins at 30° and ends at around 69°, which is later than the 2_40nm but ends earlier than the 5_40nm. The shape of the loop does not change much between 0° to 20°, 40° to 55°, and 85° to 90°. The coercivity in this sample does not change at most angles, except at 35° to 38° and 67° to 68°. The remanence follows the same pattern as the 5_40nm, where there is a decrease in remanence at around 40° and then again at around 65° (Fig. 6.9). The 5_60nm sample is also similar to the 5_40nm, where the annihilation gradually increases until about 70°. The nucleation almost shows the same feature as the 5_40nm but there is a small increase in field at around 35°, then it remains constant until there is a huge increase at about 70°. In summary, the 5_40nm and 5_60nm follow the same trends, while the 2_40nm seems to undergo the phase rotation at an earlier angle and the remanence seems to differ from the 5_40nm and 5_60nm. This could be due to the fact that in the 2_40nm the exchange coupling is not as strong as the 5_40nm and the 5_60nm, therefore this phase rotation is more likely to happen quickly and the change in the loop shape change more dramatically with angle. A summary of this phase rotation with respect to sample an angle is presented in Table 6.1. Again in this data, measurements performed up to 180° verify the uniaxial symmetry of the sample.

<table>
<thead>
<tr>
<th>Phase Rotation</th>
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<tbody>
<tr>
<td>Sample</td>
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<tr>
<td>5_0nm</td>
</tr>
<tr>
<td>2_40nm</td>
</tr>
<tr>
<td>5_40nm</td>
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<tr>
<td>5_60nm</td>
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</table>

Table 6.1: Phase rotation beginning and end angles for 5_0nm, 2_40nm, 5_40nm, and 5_60nm.
Figure 6.2: MOKE loops for 5 chain nano-dot with zero bridge width. The red line designates the loop direction from H→-H.
Figure 6.3: Annihilation and nucleation fields for each angle for the 5 chain nano-dot array. Susceptibility is calculated since remanence is zero for all angles.
Figure 6.4: MOKE loops for 2 chain coupled nano-dot with 40 nm bridge width. The red line designates the loop direction from $H \rightarrow -H$. 
Figure 6.5: Annihilation, nucleation, and remanence for each angle for the 2 chain coupled nano-dot with 40 nm bridge width.
Figure 6.6: MOKE loops for 5 chain coupled nano-dot with 40 nm bridge width. The red line designates the loop direction from $H \rightarrow -H$. 
Figure 6.7: Annihilation, nucleation, and remanence for each angle for the 5 chain coupled nano-dot with 40 nm bridge width.
Figure 6.8: MOKE loops for 5 chain coupled nano-dot with 60 nm bridge width. The red line designates the loop direction from $H \rightarrow -H$. 
Figure 6.9: Annihilation, nucleation, and remanence for each angle for the 5 chain coupled nano-dot with 60 nm bridge width.

6.2 Combination of x and y Magnetization

While these hysteresis loops were first seen unusual to us, other studies have observed similar loops in other anisotropic systems and have explained them as arising from a second-order magneto-optic effect.\(^{22}\) While we discussed above that MOKE is related to the spin-orbit interaction, the second-order is related to the spin-orbit interaction squared; therefore using this method there have been certain studies that are able to detect the two magnetization components.\(^{23,24}\) Osgood, et. al.\(^ {22}\) showed that these asymmetric loops were a combination of an


x and y-component of the magnetization and by rotating the laser polarization by 45°, the x-component would not be detected, and only the y-component would be detected. We believe that this may explain our unusual hysteresis loops, in that the angular measurement contains both the x and y-component of the magnetization.

To test this we formed a series of experiments on the 5_0nm sample, where the laser polarization was rotated at an angle $\beta$ from the incidence plane. We hope to see that only the y-component will be detected when $\beta = 45^\circ$, therefore giving insight to our unusual loops. Figure 6.10 shows the laser polarization at $\beta = 0^\circ$ and 45° and the sample rotated at $\theta = 0^\circ$ and 45°. When the sample was at 0° and $\beta = 0^\circ$ we see the expected loop as seen in Section 5.1 [Fig. 6.10(a)]. The observation of only an x-component can be explained by observing Figure 5.2, which shows that the y-component is either canceling out or absent in the dot, due to symmetry in the dot. When $\beta = 45^\circ$, no signal was detected [Fig. 6.10(b)], confirming that this $\beta$ angle is only sensitive to the y-component. Interestingly enough, when the sample was rotated to 45° and $\beta = 45^\circ$, we observe a signal, which could only be the y-component at $\theta = 45^\circ$ [Fig. 6.10(d)]. At this same rotation and when $\beta = 0^\circ$, the signal was similar when $\beta = 45^\circ$; therefore when $\beta = 0^\circ$ it is reasonable to conclude that the signal contains not only an x-component of the magnetization but also a y-component of the magnetization. Thus, we can conclude that there is an y-component of magnetization that is affecting the magnetization signal at oblique angles. This increase in the y-component can be shown by OOMMF simulations for the 5_60nm sample at rotations of 0°, 30°, 45°, and 60° (Fig. 6.11). At 0° the y-component of the magnetization is very low, but increases with increasing angle. In the snapshot of the magnetization pattern taken for the 5_60nm sample at $H = 0$ Oe [Fig. 6.11(a)], we still observe the large moment in the inner dots of the chain and the “S” shaped domain, while the outer dots have formed vortices, which is similar to the results shown in Section 5.1. Also in this snapshot, the vectorial addition of the y-component magnetization is not zero, which indicates that there is a y-component in the total magnetization.

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Figure 6.10: MOKE data for 5 chain nano-dot with zero bridge width rotated at $0^\circ$ and $45^\circ$, with a laser polarization at $\beta = 0^\circ$ and $45^\circ$. 
Figure 6.11: OOMMF simulation for 5 chain nano-dot coupled with 60 nm bridge width rotated at 0°, 30°, 45°, and 60°. (a) shows a mask rotation at 30° at zero field. An axis is drawn to indicate that the field is applied along the horizontal.
6.3 5_20nm Sample

Even though when the 5_20nm sample was first used in the MOKE, it was producing the same kind of loops as observed above, but when re-tested with the new sample holder, the data did not show the unusual loops (Fig. 6.12). We do obtain what we expect for 0° and 90°, but the only thing different we see in the angles between 0° and 90° is extra steps that appear. These extra steps can be explained by the OOMMF magnetic snapshots. When the sample is rotated the outer left dot nucleates first in the chain, then the outer right dot nucleates, which is then followed by the inner dots nucleating. With this sequential nucleation and the bridge switch that occurs as discussed in Section 5.2, this could explain the extra steps observed in these angles. This sequential nucleation is seen in all of the 5 chain coupled nano-dots and Figure 6.13 demonstrates snapshots of the magnetization of pattern of this sequential nucleation for the 5_60nm sample.

The nucleation and annihilation follow the same trend as the 5_40nm and 5_60nm, but the remanence increases from -50° to -10° and then decreases with increasing angle (Fig. 6.14). We compared these results with the x-component magnetization in OOMMF (Fig. 6.15). Again we obtain the same discrepancies as before, but the extra steps observed in the MOKE data is seen in the OOMMF simulation. In the end, the 5_20 nm is very puzzling and further studies on this sample will include investigating why the signal changed from the previous experimental data. The sample’s color is significantly different from the other samples, therefore a characterization of the sample would be helpful to see whether the sample has lost its’ photoresist protection or has undergone oxidation.
Figure 6.12: MOKE loops for 5 chain coupled nano-dot with 20 nm bridge width.
Figure 6.13: Snapshots for 5_60nm sample shows the sequential nucleation that takes place when the sample is rotated at an angle of 30°. (a) shows nucleation of the left outer dot, (b) shows nucleation of the right outer dot, (c) shows the "S" shaped domains present in the inner dots, and (d) shows nucleation of all the dots via bridge switch.
Figure 6.14: Annihilation, nucleation, and remanence for each angle for the 5 chain coupled nano-dot with 20 nm bridge width.
Figure 6.15: MOKE and OOMMF loops for 5 chain coupled nano-dots with 20 nm bridge width.

6.4 Final Discussion

For comparisons, Figures 6.3, 6.5, 6.7, 6.9, and 6.14 are combined into one figure (Fig. 6.16). Even though the uncoupled nano-dots graphs are presented in Figure 6.16, the 5_0nm sample field trends will not mirror the coupled nano-dots, since the uncoupled dots have a four-fold symmetry versus the two-fold symmetry seen in the coupled dots. In Figure 6.16, when comparing the coupled nano-dots we observe that the nucleation and annihilation fields are not affected by the unusual loop shapes, since similar features are observed in the 5_20nm as in the other coupled dots. However, the remanence is likely effected by the inclusion of the y-component in the magnetization signal. Therefore, the remanent state may provide more in depth insight into the relationship between the x and y-component of the magnetization. To understand this fully, this will require extensive OOMMF simulation, which is beyond the scope of this thesis.
Figure 6.16: Annihilation, nucleation, and remanence data for all samples 5_0nm, 2_40nm, 5_20nm, 5_40nm, and 5_60nm.
7 Conclusions

This thesis has shown that exchange coupling suppresses vortex formation along the coupling direction. When the field was applied along the coupling direction the exchange coupling energy builds up and this build-up is shown in the OOMMF magnetic snapshots as “S” shaped domains. The exchange energy is released via the magnetic moment in the bridge switching, followed by simultaneously vortex annihilation. When the field is applied perpendicular to the coupling direction little difference is seen between the isolated dot loops and coupled dot loops, due to the bistability of the bridge remanent. However in the 5 chain coupled 60 nm bridge width sample shows a remanent moment in the hysteresis loop, because the width of the bridge is now larger than the length of the bridge and due to shape anisotropy, the moment will prefer to stay normal to the coupling direction.

As expected the uncoupled nano-dots showed four-fold symmetry, while the coupled nano-dots displayed a two-fold symmetry. However, at oblique angles, unusual hysteresis loops were obtained and analyzed. The 5 chain coupled nano-dot with 20, 40, and 60 nm bridge width showed similar trends in both the nucleation and annihilation fields. The 5 chain coupled nano-dot with 40 nm and 60 nm bridge width also showed similar trends with angle in their remanence state. The 5 chain and 2 chain system showed a difference in the phase rotation, in that the rotation begins at earlier angles in the 2 chain system. The 2 chain coupled nano-dot system showed similarity in the nucleation and annihilation trends with the 5 chain coupled nano-dots with 20, 40, and 60 nm bridge width. We also showed that these unusual loops likely arise from some kind of combination of x and y components of the magnetization, which effects the remanence of the system but not the nucleation and annihilation fields. Further studies will include investigating the in-plane anisotropy by using the ferromagnetic resonance technique in a 35 GHz cavity, performing extensive OOMMF simulations to explain the interaction of the x and y-component of the magnetization at remanence, and attempting to explain the change in the experimental signal in the 5 chain coupled 20 nm bridge width sample.
References

12. Carl R. Nave, HyperPhysics: Hysteresis Loops, Department of Physics and Astronomy, Georgia State University, (2006) http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html


Appendix A
Specifications for Model 117A Stabilized Helium Neon Laser

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<th>SPECIFICATIONS</th>
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Specifications subject to change without notice

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