Switching Behavior in Ferromagnetic Nanorings

Lori-Anne Ashwood

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Katherine Aidala, Mount Holyoke College
Thesis Advisor

Department of Physics

South Hadley, Massachusetts

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Abstract

Magnetic nanorings have unique closed-flux vortex states that exhibit no stray field. The chirality of the vortex can be used to represent a ”1” or a ”0” in magnetic bits for data storage purposes. Atomic Force Microscopy (AFM) was used to gather topographical information and Magnetic Force Microscopy (MFM) to image magnetic states of asymmetric Cobalt nanorings. Eventually we seek to control the chirality of these rings by passing current through their centers, which can also be done using the AFM.

The aim of this research is to study the switching behaviors of magnetic nanorings and to prototype consistent methods of controlling the magnetic states of these rings to facilitate the possible creation of a new high density magnetic storage system.

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1 Introduction

Evolution of technology has increased storage density in storage media as a result of decreasing its overall size. This thesis is an investigation of nanorings as a possible bit element that could lead to the further compaction of information storage systems. The goal of this research is to prototype a novel solid state storage system that exploits the unique behaviors of these rings.

In depth study of the behavior of nanorings of varying dimensions facilitates the development of predictable control systems. Given control of their behavior, the physics of these rings can be optimized to develop an innovative type of high density storage device.

The behavior of these rings were studied using the Asylum Research MFP-3D Atomic Force Microscope to perform Atomic Force Microscopy and Magnetic Force Microscopy under an applied in-plane external magnetic field produced by the Variable Field Module attachment. Investigations were made about the necessary in-plane fields required to produce different magnetic states in the rings. Further investigations need to be done to facilitate control of individual rings. A proposal to use an azimuthal field produced by passing a current through the center of the rings is discussed.

2 Background and Motivation

Magnetic media provide efficient, and durable systems to store information. Many different forms of magnetic media have been previously used. Two common types are magnetic tapes and hard drives. Magnetic tapes are reliable, but require a lot of physical storage space, have a propensity to stretch and can only be used in sequential processing. Hard disk drives add the flexibility of random access information retrieval by separating the disk into bit sectors that can easily be referenced randomly, but because of moving parts, there is a delay period to getting information from the drive, slowing down performance.

Each of these forms of magnetic media store information in binary units of 1s and 0s called bits. In existing media, these bits are stored as north (N) or south (S) magnetic poles on the ferromagnetic surface of the tape or disk. Any binary system, however, can be used to store bits. Whatever magnetic configuration is used to store these bits must be coupled with some standardized mechanism to read and write information to the storage medium.

Stability and integrity of bits are two very necessary properties of data storage. Interaction between bits compromises the stability and integrity of the storage system. The bits must be positioned at distances from each other so that they will not interact.

Scientific innovations with magnetic material make it possible to develop ideas of how to create a stable, dependable, non-volatile, solid-state, random access memory storage system that should further improve the capabilities of magnetic media. An optimal system, among other things, should be compact, fast, high capacity and not susceptible to memory loss due to accidental loss of power.

The goal of this thesis is to understand and analyze the behavior of ferromagnetic nanorings with the application of external magnetic fields. Specifically, we want to consider the field created from passing current through the center of the ring in order to prototype a process that uses nanorings as functional bit elements of a possible layered high density storage system architecture.

The rest of this section will outline the background of physical concepts and previous studies on rings.

2.1 Ferromagnetism

Ferromagnetic materials are those that retain magnetization in the absence of an external magnetic field. Magnetism arises from magnetic moments, which can only be understood fully with quantum mechanics. However, they can be conceptualized as tiny bar magnets, and are generally represented as arrows pointing in the direction of a magnetic domain from the South (S) pole to the North (N) of a magnet. The magnetization of an object can be described by a set of arrows representing the alignment of internal groups of moments. (Fig. 1)

Like macroscopic magnets, magnetic moments have their own magnetic field and interact with the field of neighboring moments. Within a material, they will seek to exist in their lowest energy state which is determined by minimizing the various competing energies intrinsic to moments. The equation for the total energy associated with magnetic moments that needs to be minimized is defined as:

$$U_{tot} = U_{exchange} + U_{anisotropy} + U_{magnetostatic} + U_{Zeeman} \tag{1}$$

The exchange energy ($U_{exchange}$) is minimized when the moments are aligned parallel to one another within a ferromagnetic material (Fig. 1a). It is defined by the following equation:

$$E_{exch} = -\sum_{<ij>} J\vec{S}_i \cdot \vec{S}_j \tag{2}$$

where J is positive constant for ferromagnetic materials and represents the ferromagnetic coupling that aligns spins parallel to each other. S_i is the total spin of all the electrons bound to the atom, or ion at the lattice site i. Spin, in these definitions, is a quantum mechanical property of particles that affects their behavior in a magnetic field.

The exchange equation (Eq. 2) is a negative dot product of neighboring spins in a material. It is minimized when S_i and S_j are parallel to each other (because $\vec{S}_i \cdot \vec{S}_j = S_i S_j \cos\theta$, where $\theta =$ the angle between S_i and S_j, and when S_i and S_j are parallel $E_{exch} = -J\left|S_i\right|\left|S_j\right|$)

The exchange interaction is a strong but short ranged force. It affects nearest neighboring moments. It depends on relative angles of spins, not absolute orientation of spin. It is isotropic which means that the direction of the spins in relation to the lattice of the material does not affect the exchange interaction.

While exchange interaction is isotropic, some magnetic materials have a preferred direction of magnetization. The anisotropy energy ($U_{anisotropy}$) arises from a material property that identifies the preferred direction for the moments to align along a given crystal axis. The most common type of anisotropy in magnetic materials is magnetocrystalline anisotropy, which is caused by the spin-orbit interaction. Electrons of an atom orbit the positively charged nucleus. The interaction of electron orbit and spins causes the spins to prefer to align along well-defined crystallographic axes. This preferred alignment produces a situation where there are directions in which it is easier to magnetize a given crystal than in others. The anisotropy energy is small compared to exchange energy and is temperature dependent. Not all materials have this property. Some materials like permalloy, have zero anisotropy.

The magnetostatic, or demagnetization, energy ($U_{magnetostatic}$), is the energy contained in the magnetic field outside of a magnetic material due to its own internal magnetization. It increases with the volume of the field. A piece of material with a single domain will have a large external magnetic field. The material could reduce this energy by forming areas where different domains exist that are separated by domain walls within its structure at the cost of the exchange energy so that the magnetic field will loop inside the material, reducing the external field(Fig. 1b).

The equation for magnetostatic energy is:

$$E_M = -\frac{1}{2}\int \vec{M} \cdot \vec{H} d\tau \tag{3}$$

where $\vec{M}$ is the magnetization of the material, or the volume density of the magnetic moment and $\vec{H}$ is the magnetic field strength of the magnetizing field (i.e. 'external' field). The E_M is minimized when the direction of the magnetization of the magnetic moment, μ, is antiparallel with the direction of the magnetizing field, which may be the influence of neighboring moments within the surface of a material. This energy is dependent on the shape of the material and is anisotropic in nature. However, a material with low anisotropy can have flux-closure domain patterns.

We are accustomed to thinking about charge being a source of electric field lines. Similarly, given magnetization , $-\nabla \cdot \vec{M}$ and $\vec{n} \cdot \vec{M}$ where $\vec{n}$ is a vector normal to the plane of the material, form 'virtual magnetic charges' that produce stray fields outside a material. These are virtual charges because magnetic flux is always zero because they always exist in loops and there is no magnetic monopole.

The Zeeman energy (U_{Zeeman}) is denoted by the equation:

$$E_H = -\int \vec{M} \cdot \vec{H}_{ex} d\tau \tag{4}$$

and is minimized when the moments align with an external field ($\vec{H}_{ex}$) (Fig 1c).

One of the factors that affects energy minimization is the shape of the ferromagnetic material. Given the ultimate goal of this project to create stable bit elements for a high density storage system, a geometry that minimizes external stray field (i.e. minimizes $U_{magnetostatic}$ and interaction between ele-

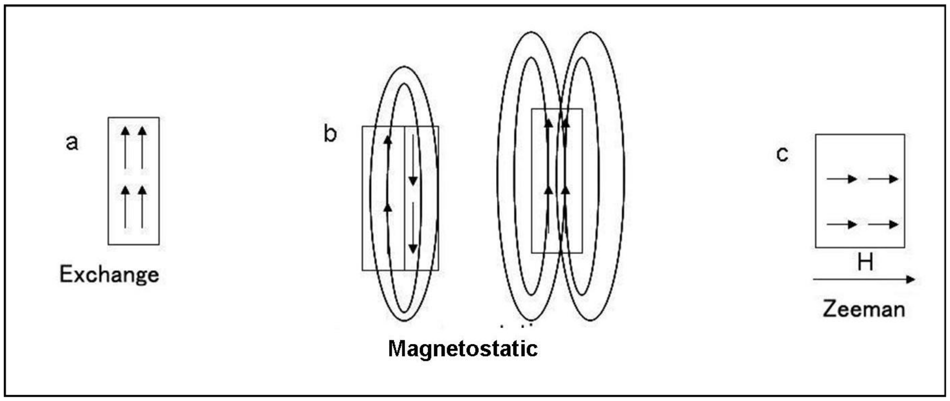

Figure 1: *A visual representation of the how moments may align to minimize (a)the exchange energy, by parallel alignment, (b)the magnetostatic energy, by antiparallel alignment with a domain wall separating opposite domains to reduce field lines and (c)the Zeeman energy, by alignment with an external field.*

ments) is required.

2.1.1 Evolution in Time

Ferromagnetic materials retain their magnetization in distinct states. This magnetization can evolve over time when changing from an unstable (intermediate) state to a stable (remanent) state. This evolution can be described by the precessional motion of magnetization M in a solid. This is mathematically written as the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{d\vec{M}}{dt} = |\gamma|\,\vec{M} \times \vec{H_{eff}} - \frac{|\gamma|\,\alpha}{M_s}\vec{M} \times \vec{M} \times \vec{H}_{eff} \tag{5}$$

where γ is the electron gyromagnetic ratio and α is the Gilbert phenomenological damping parameter. This equation defines the torque on moments in an area with a damping constant that was discovered in previous studies. The resultant alignment of the moments determines the value of the magnetization over time.

2.1.2 Hysteresis

One of the properties of ferromagnetic materials is that they retain a magnetization even in the absence of an external magnetic field. The magnetization of these materials is determined by the alignment of their magnetic moments. It can be reordered by a strong external switching field that causes the Zeeman energy to dominate the energy minimization equation and cause the moments to realign in a different state. Figure 2 is an example of a history of the magnetization of a magnetic moment. The curve formed is known as a hysteresis curve. The x axis of this curve represents the strength of the external applied field and the y axis represents the magnetization of the material each in arbitrary units. The graph shows a moment magnetized by a positive external magnetic field which is denoted by the upward arrow. The magnetization of the moment (at A) cannot be changed by an increase in this external magnetic field. The moment by virtue of its ferromagnetism retains its saturation mag-

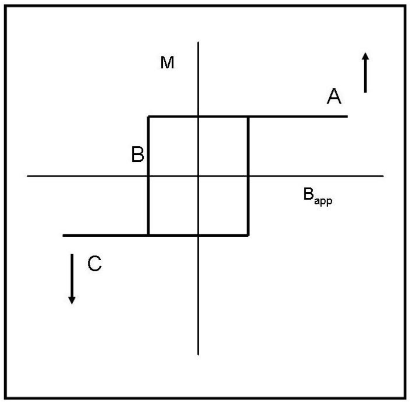

Figure 2: *Schematic of hysteresis curve for a magnetic moment*

netization even after the external field is decreased back to zero. To reverse this magnetization, the external magnetic field must be increased negatively. The material passes through zero magnetization as it flips vertical directions at some negative external field (at B) rather than at zero external field because of its characteristic retention of magnetization. In the negative direction (denoted by downward arrow), it also reaches some saturation point (at C) where it maintains a remanent magnetization even as the negative field is decreased to zero external field. Again, some positive switching field is needed to change the direction of this saturated magnetization state.

The hysteresis of a material can give insight into the possible states of a particular structure and properties of the material or device. A wide curve shows that it is hard to switch the states of a material (it requires a large applied switching field). While a curve with distinct variations in it shows that there are well-defined intermediate states, as will be seen for nanorings.

2.2 Nanorings

Small ferromagnetic disks and rings have a closed-flux vortex state (Figure 4) in which the moments align circularly in the material. The circular orientation of the moments incur an exchange energy cost because the moments align at slightly non-parallel angles. However, the magnetostatic component dominates the minimization equation as the field lines of moments in this geometry are kept within the boundaries of the material reducing the stray field to zero.With zero in-plane stray field, there is little possible interaction between neighboring rings.

While they both have circular geometries, disks and rings are different magnetically. In the vortex state of a disk, the exchange energy is dominant at the center causing the center moments to pop out of the surface plane to align parallel to each other to create an out-of-plane vortex core which produces an orthogonal magnetic stray field (Fig. 3). Rings eliminate this core and the stray fields it produces, by cutting out the disk center.

Research of nanorings has identified various magnetic states, which can

Figure 3: *Perspective view of the magnetization of a clockwise vortex structure of a disk with moments popping out-of-plane to form a core due to exchange interaction of closely packed anti-parallel aligned moments at the center (Ref. [2])*

be understood by thinking about the competing energy terms. (Figure 4) The vortex state(Figure 4a and b) exists in counterclockwise and clockwise vortices that have the same energy and thus can be considered degenerate states.The direction of the vortex, often called the chirality, does not affect the total energy cost.

The dipole/single domain state (Figure 4c) will exist at large in-plane external magnetic fields and at zero field for very small rings [3].

The onion state (Figure 4d) is a two-domain state with semicircular magnetizations of different chirality separated by two domain walls where the opposing magnetizations meet.

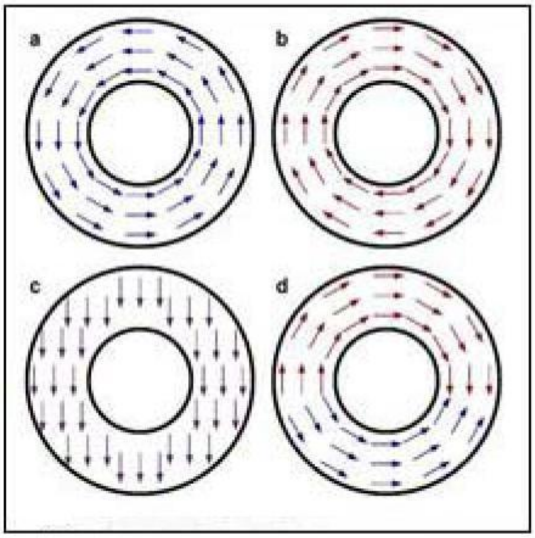

Figure 4: *States of ferromagnetic nanorings. (a) Counterclockwise vortex (b)Clockwise vortex (c)Single domain dipole (d)Two domain onion*

2.2.1 Factors Affecting Switching in Nanorings: Symmetry and Size

The symmetry and size of a ring determines the magnetic states it will form, the stability of these states and the energy needed to switch between states. [4] Understanding which states will occur and being able to predictably determine the formation of vortex states is important in standardizing a read/write system for a storage device.

Research [5] has shown that for disks approximately 300nm wide in diameter and 10 nm thick that the vortex state will reliably occur. It also shows

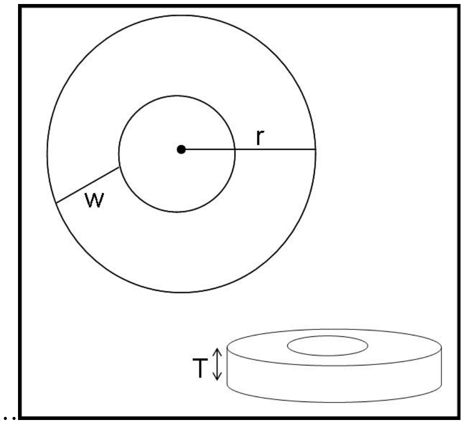

Figure 5: *Dimensions of rings*

decrease in these parameters can increase the probability that the disks will act as single dipoles. This behavior has been attributed to the influence of the vortex core.

In thin magnetic rings (with T as little as 5nm), the vortex state is stable if the radius r of the ring is small (as small as 50 nm) and the width of the ring is narrower that the width of a domain wall for that material which is about 50nm in Cobalt [7].

According to Zhu [7], the size of the ring will also determine whether or not it will have a remanent vortex state. The graphs in figure 6 show the two possible hysteresis loops for rings. For large rings (approximately above 50 nm in radius), the onion-vortex-onion process (V process)(Fig. 6a) is dominant and is more likely to occur (almost 100% of the time). For smaller rings, the domain walls (DWs) of the onion state may simply rotate away from each other instead of colliding to produce a onion-onion rotational switching process (O process)(Fig. 6b). In these smaller rings both the V and the O processes are likely.

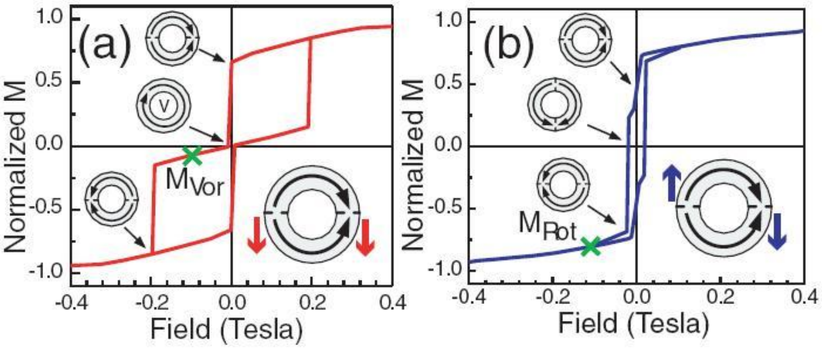

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Figure 6: *(a)Hysteresis of a ring that undergoes the V Process with domain walls (DWs) moving toward each other to annihilate into a vortex state. (b) Hysteresis of a ring that undergoes the O process with DWs moving away from each other essentially rotating the onion state around the ring. (Ref. [7])*

The symmetry of the ring also affects its switching behavior. Symmetric and asymmetric exhibit the same intermediate and remanent states, but when using in plane magnetic fields it is not possible to control the direction of the chirality of the vortex in symmetric rings.However, the asymmetry of a ring can allow control over the chirality of its vortex state.

When an external field is applied to the ring along the axis of asymmetry (Fig. 7), the moments in the material try to align with the external field to create an onion state. The points where the ends of the arrows meet at the end of the major axis of the ellipse, form domain walls (DW) between 2 semicircular magnetizations of opposite chirality - counter clockwise on the bottom half and clockwise on the top. This state of the ring corresponds to the positive magnetization of the hysteresis in Figure 6a and represents the saturated magnetization state of a ring.

When the field is decreased, the two DWs move. In rings that relax using the V process, an asymmetry can be used to control the direction of the DW movement as they will move towards each other and collide to form a vortex state. The direction of the DW is controlled by the gradient of the DW energy or of the ring width along the circumference (Fig. 7aii). Both of the DWs will move toward the narrower semicircle of the ring to reduce DW energy [6], since a shorter wall will cost less energy. Consequently, the direction of the circulation in the resultant vortex state (counterclockwise) is determined by the applied magnetic field. If the field were applied in the opposite direction, the opposite onion state (Fig. 7b i) would form. A decrease in that field would result in an similar DW annihilation (Fig. 7bii) where the chirality of the lower half of the ring (CW) grows to form the final chirality of the ring (CW) (Fig. 7biii)

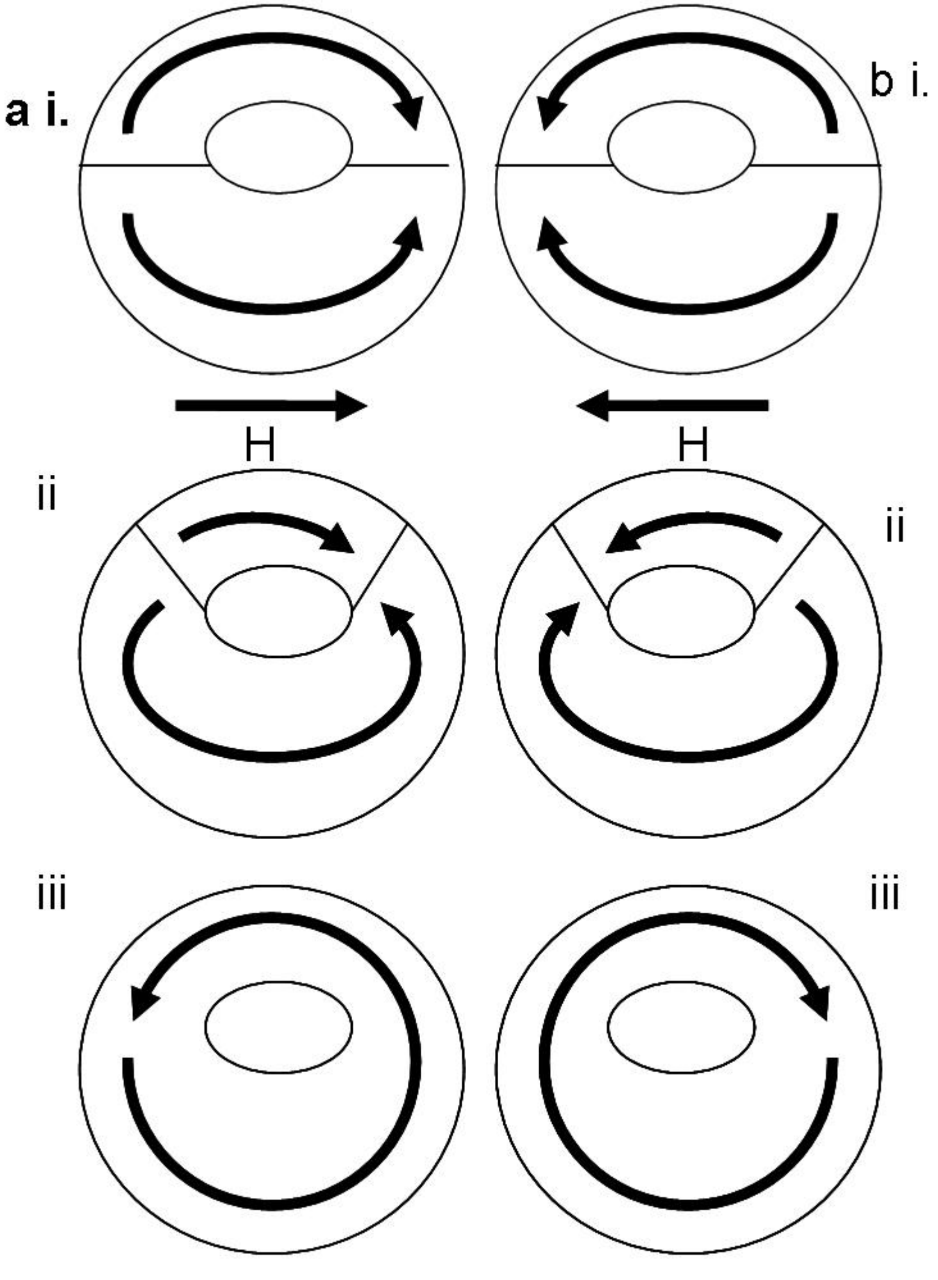

Figure 7: *Conceptual diagram of how asymmetry in rings controls the chirality of the remanent vortex state depending on the direction of the applied field along the axis of asymmetry*

3 Technological Motivation

The goal of this project is to measure and to prototype a method of controlling the states of nanorings. Control and study of the switching between the vortex states in individual rings using an in-plane field gives us information about the general behavior or rings. Control of the state of individual rings could provide various avenues for technological application like information storage. A possible method of individual ring control is to pass a current through the ring center to directly apply an azimuthal field (Fig. 8).

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Figure 8: *Passing current through a wire creates a radial magnetic field that can be used to influence the chirality of nanorings*

3.1 Technical Applications

3.1.1 Magnetoresistive Random Access Memory(MRAM)

A novel type of data storage device [8] has been proposed that utilizes the unique behavior of magnetic nanorings and magnetoresistance to create bit elements. Magnetoresistance is the property of a material to change the value of its electrical resistance depending on the external magnetic field applied to it. Figure 9 is proposed version for a bit element for a random access memory storage system that uses magnetoresistance. When the reversible ferromagnetic ring has the same chirality as the pinned ring the effective resistance is less than when it is of opposite chirality. The difference in resistance would be the binary to define bit elements. These could be written by passing a current through the center to change the chirality of the reversible ring and read by passing a current to find the resistance. This is only one of possible applications towards which this research could be used.

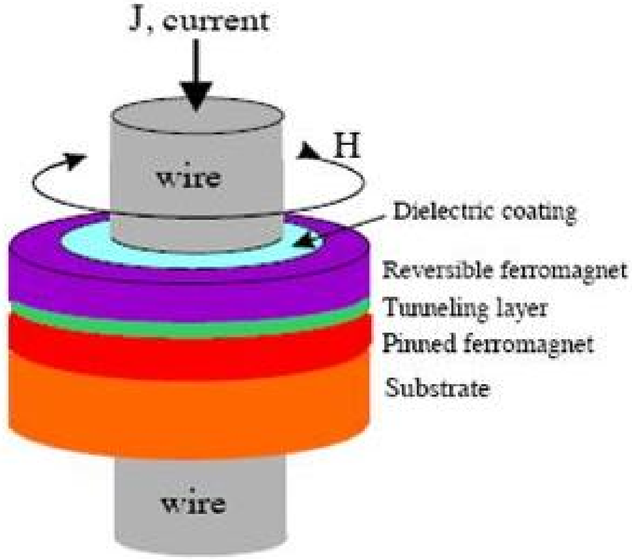

FIG. 1: Schematics of the proposed design.

Figure 9: Schematics of the proposed design from [9]

4 Experimental Techniques

Scanning Probe Microscopy (SPM) is a very versatile and flexible type of microscopy. It enables the investigation of submicron-scale objects. Optical observation techniques fail to achieve the necessary resolution to properly capture the features that exist at this scale and also cannot capture magnetic information. Conversely, SPM techniques have the advantage of being able to measure topography as well as measure and manipulate magnetic states at this scale. It also resolves 3-dimensional surface images because data is acquired by physical interaction with the sample. SPM enables examination of individual variation of rings and can enable us to test whether or not there is a topographical connection to magnetic states. The SPM techniques that were used on our samples were Atomic Force Microscopy (AFM) and Magnetic Force Microscopy (MFM). The external in-plane magnetic field was produced by a Variable Field Module (VFM). Additionally, Conductive-Atomic Force Microscopy (C-AFM) was to have been used to pass current through the center of the rings had time permitted. The Asylum Research MFP-3D Atomic Force Microscope (AFM) was used to perform all these techniques.

4.1 Atomic Force Microscopy

Atomic Force Microscopy is a high resolution type of scanning probe microscopy (SPM) that gathers information by ”feeling” the surface of a given sample with a mechanical probe. It is capable of resolutions on the nanometer scale and can be used for imaging, measuring and manipulating matter on the nanoscale. A cantilever with a sharp tip (Fig 10) is used to scan the topography of the sample surface, changing the position of the reflected beam from the laser in the quadrant photodetector, giving the console feedback about the sample and the necessary adjustments to be made to the stage to maintain experiment conditions.

In intermittent contact mode, the AFM mode we use for our samples, the cantilever is driven by the AFM controller to oscillate up and down close to its resonant frequency. The amplitude of the oscillation is typically hundreds of nanometers. Interaction of short range forces, like Van der Waals forces for example, acting on the cantilever as the tip gets close to the sample surface, causes the amplitude of the oscillation to decrease. In order to maintain a set cantilever amplitude, the stage that the sample is on will adjust its height as the scan is performed. The resultant image that is rendered is the imaging of the force of the oscillating contacts of the tip with the sample surface.

Tapping mode is useful and preferable to other modes as it minimizes sample damage because of the limited contact between the tip and the sample while still providing a three dimensional surface profile of the sample. The nanorings observed in this research were examined using tapping mode AFM.

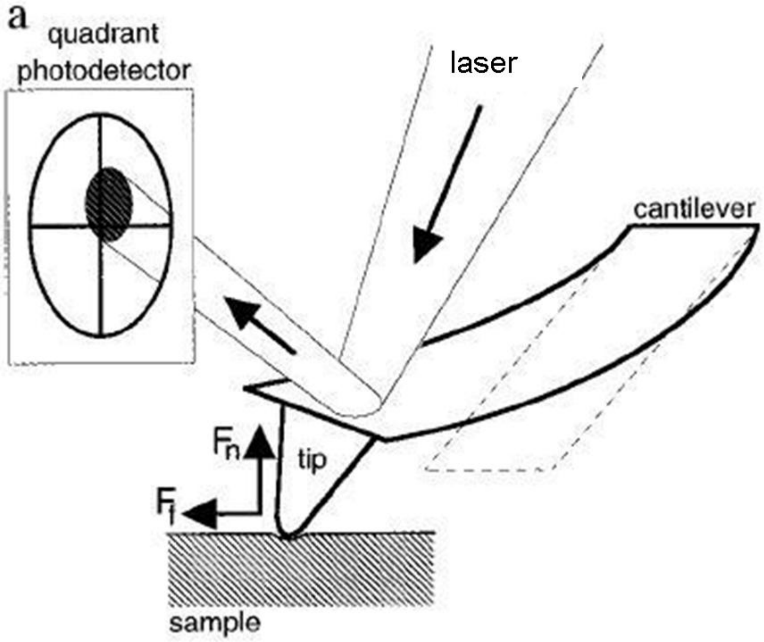

Figure 10: *Diagram of the AFM gathering information from the sample. The position of the reflected beam in the quadrant photodetector gives feedback to the console to determine the height of the stage relative to the oscillating cantilever and tip*

4.2 Magnetic Force Microscopy

Magnetic Force Microscopy is a type of atomic force microscopy that uses a magnetic tip to gain information about a magnetic sample by mapping out the long range magnetic interactions between the sample and the tip which is held at a fixed height above the sample. An MFM image is done in two passes. On the first pass, the magnetic tip performs tapping mode atomic force microscopy on the surface of the sample to measure the topography of the sample. On the second pass, the tip is raised to a fixed height and oscillated as in tapping mode. The resultant image of the second pass is the mapping of long range force interactions between the sample and the tip. In this context, the magnetic force interactions should dominate. The contrast of the MFM image is the rendering of the phase shift of the cantilever oscillations under the gradient of the magnetic field.

The force between the sample and the tip is defined by:

$$\vec{F} = \mu_o(\vec{m} \cdot \nabla)\vec{H} \tag{6}$$

where $\vec{m}$ is the magnetic moment of the tip (approximated as a point dipole), $\vec{H}$ is the magnetic stray field from the sample surface, and $\mu_o$is the magnetic permeability of free space.

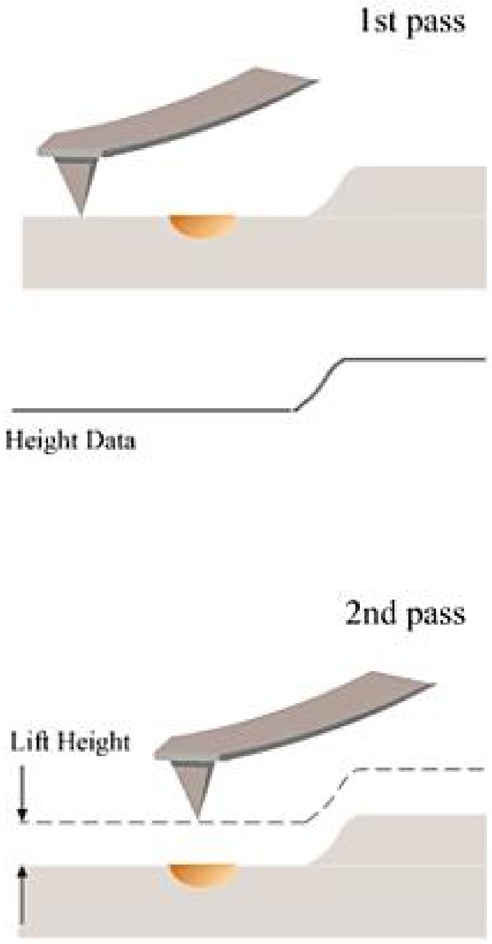

Figure 11: *Schematic of Magnetic Force Microscope on its first (topographical) and second (magnetic) pass. On the first pass the tip maps out the contours on the sample to produce height data. On the second pass the tip follows the contours of the height data and a fixed (lift) height to map out long range magnetic tip-sample interactions.*

The sample-tip force is proportional to the gradient of the magnetic stray fields of the sample. If a sample has not stray fields (like symmetric rings with perfect vortex states) it is difficult to gain magnetic information using the MFM. Thus, lack of contrast in MFM images of rings is usually assumed to mean that the ring is in vortex state. Asymmetric rings should not have perfect closed-flux vortices and should show some amount of contrast in imaging.

The frequency shift of the cantilever oscillations due to the force of the tip produces the information to create the MFM image. The calculation on the frequency shift is:

$$\frac{\Delta f}{f_0} = \frac{1}{2k_L}\frac{\partial F}{\partial z} \tag{7}$$

where f is frequency and k_L is the force constant of the free cantilever. The resultant image does not directly map the state of our sample, but the gradient of the its field. As a result we use simulations to try to make sense of the acquired data.

In our experiment, the second pass amplitude was set to half of the driven amplitude used to get the topography.Figure 12 is an example of an MFM scan. Figure 12A is the topographical information and figure 12B is the magnetic information.

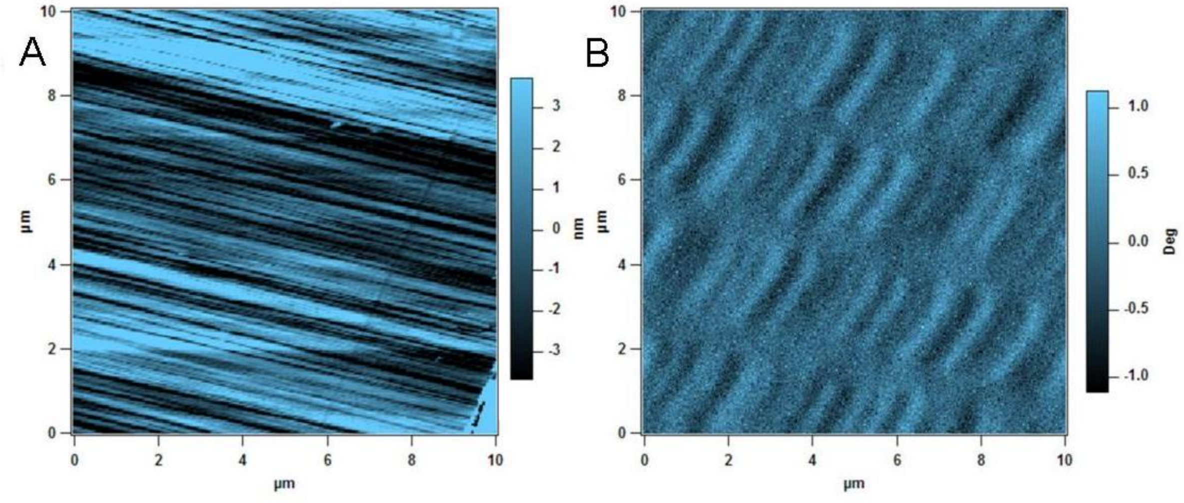

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Figure 12: *Topographical (a) and magnetic (b) images of hard drive sample*

4.3 Applying an External Field: Variable Field Module

The Variable Field Module (VFM) from Asylum Research makes it possible to apply external in-plane external magnetic fields ”exceeding ±2,500 Oe[1] with <1 Oe resolution” [10]. While electromagnets make it possible to create magnetic fields of different strengths by varying electric current, they tend to heat up, which can cause drift in images because of changes in temperature. The electromagnet’s temperature can also affect its ability to sustain its applied field, which could translate to data acquisition inaccuracies. The VFM,

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[1] a small iron maagnet has a field of about 100 gauss

instead of using electricity, uses rare earth magnets mounted with adjustable pole pieces to enable maximum field variation that can be sustained indefinitely. Because the AFM equipment and the VFM are produced by the same manufacturer there is a seamless interaction between machines, enabling field intensity to be controlled by the same software as that for data acquisition. An integrated Gaussmeter enables quantitative measurement of the applied magnetic field at any time.

4.4 Conductive - AFM

The AFM that was used to gather the topographic and magnetic information could also be used to pass current through the rings by using a solid metal tip instead of a coated semiconductive tip, using Conductive AFM (C-AFM). A solid metal tip is preferable in this case, as the predicted high current would only serve to melt the tip coating off of the regular AFM tips. The sample would be placed on a gold coated conductive slide and held there using a conductive fastener like silver paint. The slide which was prepared for experimentation, was fitted with a wire lead with the necessary resistance (estimated at 10M) to be connected to the external voltmeter that would be used to monitor the values coming out of the AFM. See Fig. 13.

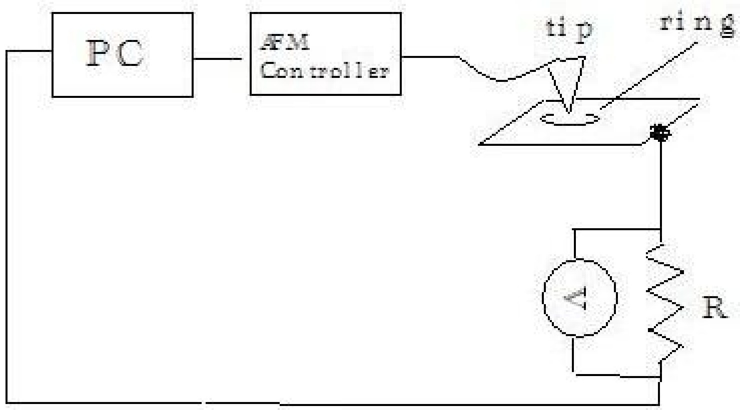

Figure 13: *Schematic of apparatus to pass current through nanoring*

The current (I) can be easily calculated using this equation:

$$I = \frac{V}{R} \tag{8}$$

In passing current, the most important parameter is the current density being applied. A reasonable current density has been estimated at 7x1010A=cm2.

5 Fabrication of Samples

The nanorings were made by Mark Tuominen's lab at the University of Massachusetts, Amherst campus. They were fabricated using electron beam lithography. The substrate was spin-coated with an e-beam sensitive material called a resist (typically poly(methyl methacrylate) (PMMA)). An area was then selected (exposed) by writing a pattern using the electron beam. Unwanted areas of the resist were removed (developed) and the magnetic material, Cobalt for our rings, was evaporated on top of the developed resist. Then the resist and all the material that landed on top of it was removed, leaving only the evaporated material that landed directly on the substrate (Fig 5). Our rings were then coated with gold to prevent oxidation.

Different sized rings can be fabricated using this method.We started with larger rings because they are easier to observe and more likely to exhibit the vortex behavior in which we are interested. Larger rings also have larger holes in their centers that can reasonably accommodate the AFM tip to pass a current.

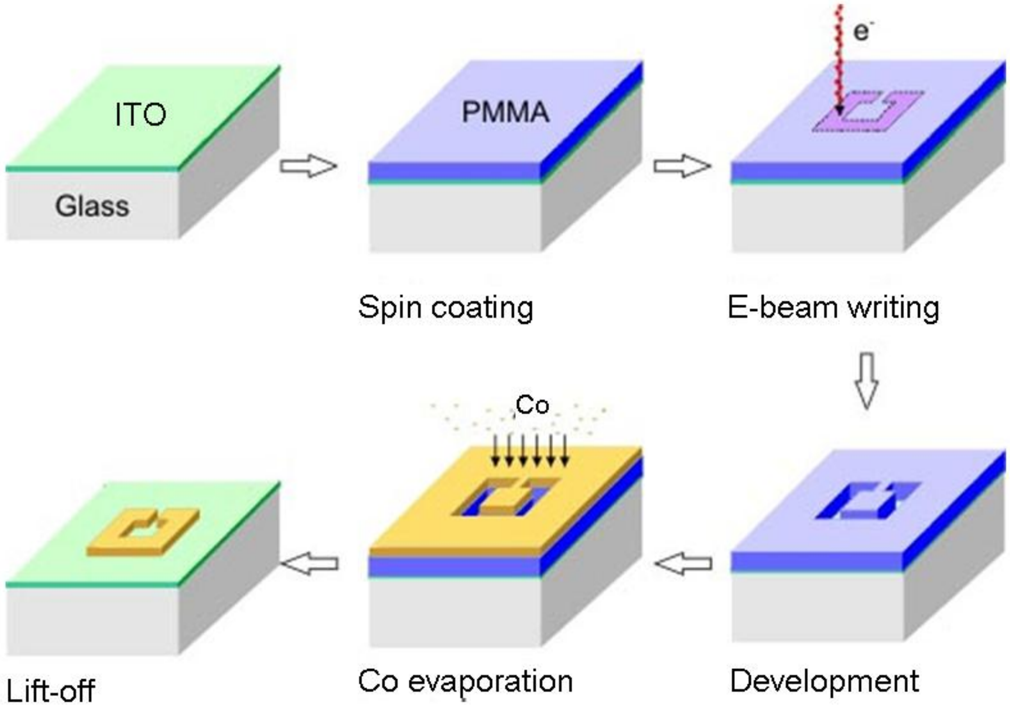

Figure 14: *Schematic of the steps for e-beam lithography which was used in the fabrication of our ring samples*

6 Results

Experiments in the lab yielded interesting results which are only preliminary steps, focusing on the first images of the evolution of states in nanorings using our experimental setup. They represent the first time magnetic states have ever been examined in our lab. Relatively large rings were chosen for these first experiments as they are easy to work with. Additionally, simulations had not yet been done to determine the size of rings that should be studied.

With the equipment set up for MFM scanning with varied field using the VFM, multiple scans were taken of the sample at different external magnetic fields. An applied external magnetic field applied to the rings effects their magnetic state. An in-plane field (as one produced by the VFM) can affect the dominating energy term and cause different types of behavior to occur in rings. For example, if the VFM field is high enough to cause the exchange energy to dominate, a single dipole domain state will emerge (Figure 4). The topographical image (fig. **??**) shows the 60nm thick rings with a $2mu$m diameter on a silicon substrate. Examination of the rings show ridges on the rings due to imperfect fabrication. This image is a small view of the smoothest rings in the array of rings provided to us by the Tuominen lab.

Different states of the rings can be observed by changing the magnetic field in stages from a positive field to a negative field. Magnetic behavior (Figure

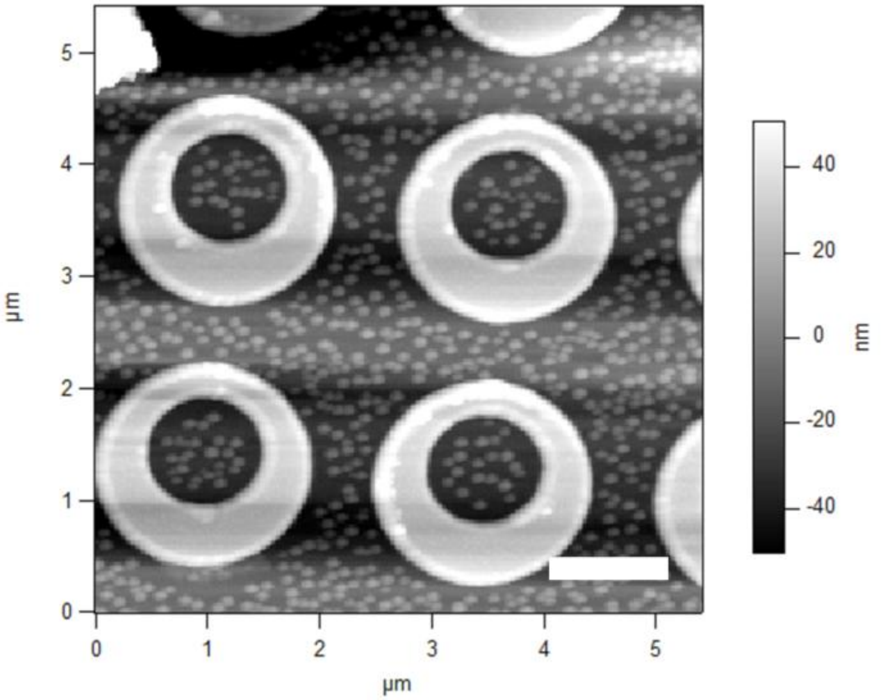

Figure 15: *AFM image of rings 60 nm in height and 2 microns in width.*

16) was observed when applying fields from -2500G to 1700G; it shows the three observed states from the stepwise changing of fields.

Figures 16a and 16b show an onion state in the arbitrarily assigned left direction for a negative field with the bright region on the rings representing one pole (S) and the dark region representing the other (N). As the external magnetic field is reduced to zero the brightness of the contrast decreases as the moments in the rings relax into their remanent vortex state. At 0G, the contrast is very faint and possibly represents the vortex state with a given chirality (clockwise by the given assignments. Refer to Fig 7 bi-iii). As the magnetic field is increased to 1700G, the direction of the onion state switches as well as is expected by the hysteresis in fig. 6a.

6.1 Discussion

The experiments had unexpected intermediate results. All the rings did not always change at the same time as the magnetic field was being varied. This may have been due to imperfections in the fabrication of the material. The MFM is particularly useful in identifying these variations and can enable us to correlate topography to the behavior of our rings.

Some of the rings have ridges of excess material which could possibly interact

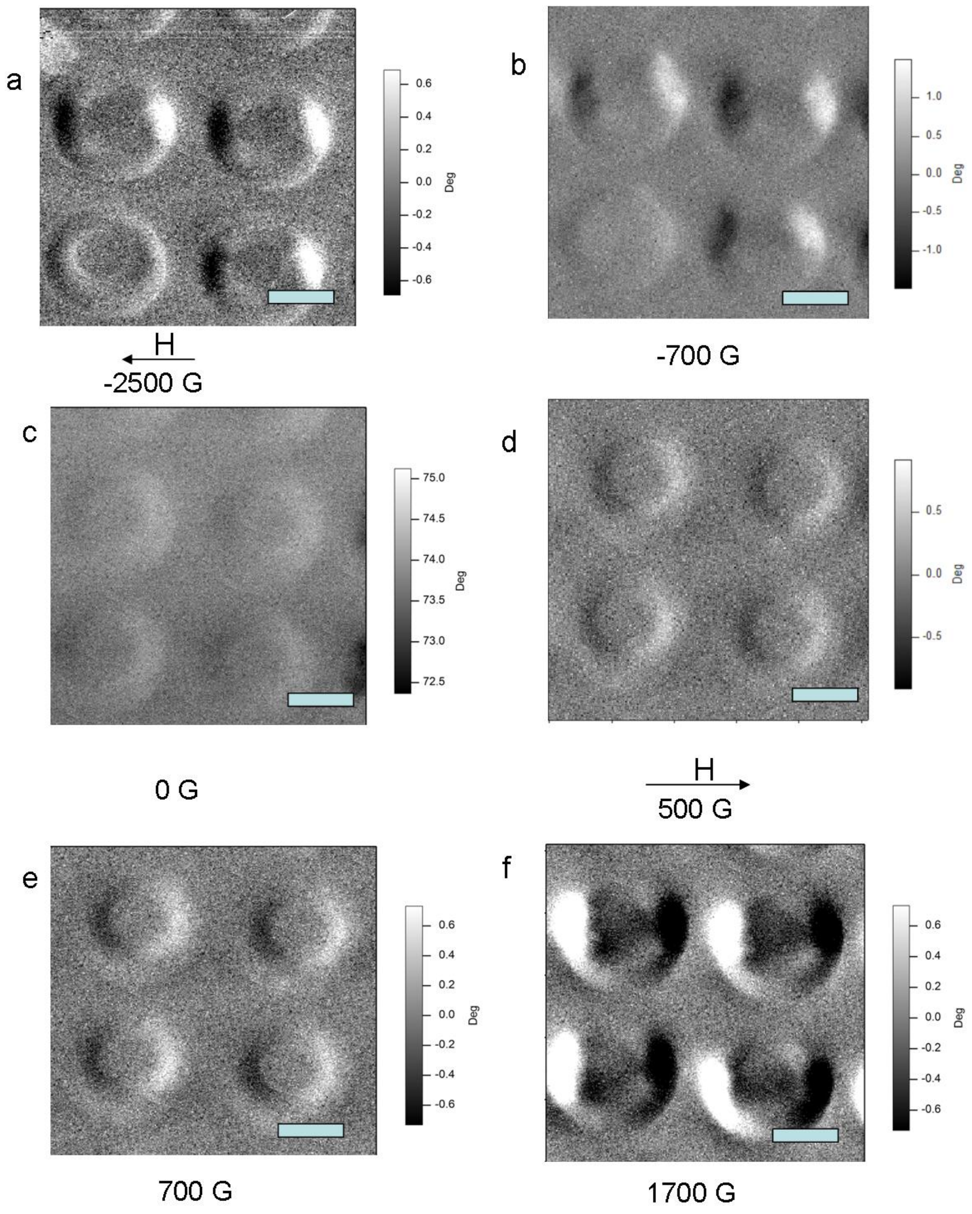

Figure 16: *MFM images of ferromagnetic nanorings at different horizontally applied in-plane fields showing the evolution from an onion with moments pointing left (in direction of applied field), to a vortex, then back to an onion with moments pointing right (again in the direction of the applied field) . The bar represents 1 micron.*

with the tip as it is taking measurements and that could also generally influence the hysteresis of the ring itself. The effect of irregularities on the sample on the tip is not entirely known, but could possibly be studied in future research.

The tip which is magnetized always has the possibility of affecting the state of the ring. There were scans where the magnetization of the rings seemed to flip during scanning (Fig. 17). It is not known if the tip could accidentally flip the state of the ring or if there is some underlying physical interaction affecting the sample. It is possible that some interesting physics is happening (like seeing the DW move) at the interim magnetizations as the VFM is being adjusted to its next setpoint. Using smaller steps will help determine whether or not this is true.

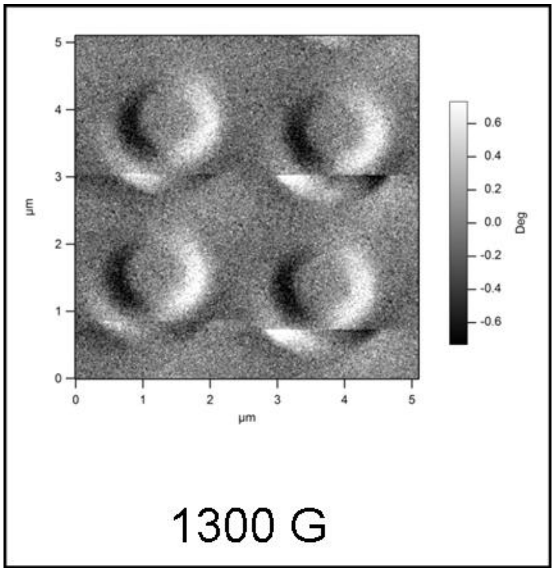

Figure 17: *MFM image of irregular scan where the magnetization of the rings change midscan*

7 Future Directions

7.1 Passing Current

The AFM tip was to be used as a conceptual current carrying conductor to produce the field needed. Simulations in our labs using micromagnetic modeling software [11], showed that the necessary current needed to flip rings of the same dimensions as our samples would be unreasonably large. For a 20nm thick ring, simulations done by a labmate, say the current needed is around 100mA, which would be an unreasonably high current density for our system and would melt the tip and possibly adversely affect the sample. The current could be pulsed to reduce the heat produced by passing a current. This would decrease the likelihood of the tip melting. The moments of the rings should respond quickly enough to make this method viable.

Nevertheless, a melted tip would become blunter but should still enable detection of rings on our sample and should still be able to pass current. The resultant current density would change but could still be effective. A reasonable current density has been estimated at $7x10^{10}A/cm^2$. The value of the necessary flipping current was not yet experimentally tested by the time of writing.

A current of 10mA was successfully passed through solid metal tip using our equipment. It was not used to further image but it is assumed that it will be possible. Simulations predict unreasonable values of current densities but usually represnent an overestimate to actual experimental results. It is possible that actual experiment will effectively switch the magnetic state of a ring at lower current densities. This hypothesis must be tested.

If the tip does melt and get blunt, it will increase in diameter. It may be necessary to use bigger rings to accommodate the large tip in the center. Big rings will require more energy to flip but if they are thin film rings this may not be a sizeable increase in energy. Once the physics is understood the tip and ring sizes may be adjusted accordingly.

7.2 360 ° Domain State

Along with the onion state, vortex and single domain dipole state, there is the 360 ° domain state, that occurs in 5nm thick rings. Research[9] has been done to test the viability of these as storage bits. The energy to move the 360 ° domain wall is a lot less than that required to produce a vortex state. These states have been found to be stable and could be a good option for bit storage in future Magnetoresistive Random Access Memory(MRAM) systems.

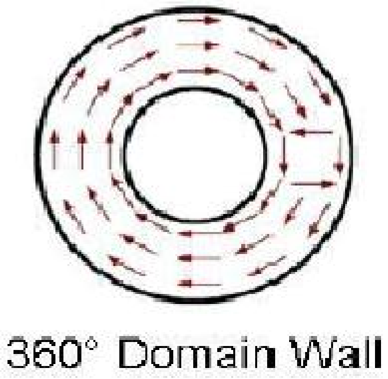

Figure 18: *Simulated* 360 ° *domain state*

8 Conclusion

This project found promising results towards understanding the switching behavior of nanorings. Experimental results using in-plane fields created magnetizations that matched the hysteresis simulations for the onion-vortex-onion curve found in previous research [7]. It should be possible to pass current through the center of the rings to control the vorticity of individual rings using the equipment in our lab.

Further experiments need to be done to understand the parameters that determine the switching field of rings and to master control of the chirality of symmetric rings. Whether or not imperfect fabrication or tip-sample interactions affect the switching behavior of rings is still unclear, but deserves some amount of investigation. Future work should include more simulations on the size of rings as well as the required current densities to switch them.

Once control of individual rings is achieved, an read/write system can be developed to control an array of these rings to produce a high density storage system. While the rings in this research are too large to considerably reduce the size of a bit element to improve on existing systems. It gives us good insight into the underlying physics of ring behavior. Given adequate research, the results could revolutionize high capacity storage systems.

References

[1] J. Yu. *Magnetic and Transport Studies of Thin Film Ferromagnetic Nanostructures*, (PhD dissertation, New York University, (2000)).

[2] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A.Thiaville and T. Ono. *Electrical switching of vortex core in a magnetic disk*, Nature Materials 6, 270 - 273 (2007)

[3] D.K. Singh, R.V. Krotkov, H.Q. Xiang, T. Xu, T.P. Russell, and M.T. Tuominen.: *Arrays of ultrasmall metal rings*, Nanotechnology 19, 245305(2008).

[4] F. Giesen, J. Podbielski, B. Botters and D. Grundler. *Vortex circulation control in large arrays of asymmetric magnetic rings*, Phys. Rev B 75 184428 (2007)

[5] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, and M. E. Welland. *Single-Domain Circular Nanomagnets*, Phys. Rev. 83, 5 (1999)

[6] E. Saitoh, M. Kawabata, K. Harii, and H. Miyajima. Manipulation of vortex circulation in decentered ferromagnetic nanorings, J. Appl. Phys., 95, No. 4, (2004)

[7] F. Q. Zhu, G.W. Chern, O. Tchernyshyov, X. C. Zhu, J. G. Zhu, and C. L. Chien. *Magnetic Bistability and Controllable Reversal of Asymmetric Ferromagnetic Nanorings*, Phys. Rev. 96, 027205 (2006)

[8] J.G. Zhu, Y. Zheng and G. Prinz. *Ultrahigh density vertical magnetoresistive random access memory (invited)*, J. Appl. Phys., 87, 6668 (2000)

[9] C.B. Muratov, V.V. Osipov: *Bit Storage by* 360° *Domain Walls in Ferromagnetic Nanorings*, arXiv:0811.4663v1 [cond-mat.mtrl-sci] (2008)

[10] http://www.asylumresearch.com/Products/VFM/VFM.shtml

[11] M.J. Donahue and D.G. Porter. *Object Oriented Micromagnetic Framework.* (National Institute of Standards and Technology: Gaithersbrug, MD) at <http://math.nist.gov/oommf/>

[12] AG Wegener, Prof. Soukoulis, Priv. Doz. F. Schmidt. *Metamaterials for Optical Frequencies* (Institut für Angewandte Physik) at <http://www.aph.uni-karlsruhe.de/wegener/?id=31&language=en>