MAGNETO-OPTICAL KERR EFFECT

STUDIES OF HALF-METALLIC CrO_2

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science with Honors in Physics
from the College of William and Mary in Virginia,

by

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Accepted for _____

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Abstract

Half metallic ferromagnetic materials are a class of materials that, due to their band structure, are conducting for one type of electron spin (spin up) and insulating for the other (spin down). [1] The conductivity (or resistivity) of these materials is referred to as 100% spin-polarized (with 100% meaning that all the conduction occurs with only one spin state). There is a great deal of interest in these materials, as it may be possible to use them to enhance the performance of magnetic storage media.

Thus far, it has been difficult to measure the half-metallic characteristics directly. Various experimental probes have been used, including point contacts. Optical techniques, especially pump-probe ultrafast laser spectroscopy, may be useful for directly probing the magnetization, bandstructure and half-metallic nature of these materials. The first step is to directly detect the magnetization of half-metals by the magnetooptical Kerr effect (MOKE). In this thesis work, we employed the magnetooptical Kerr effect (MOKE) and pump-probe ultrafast laser techniques to probe the magnetic behavior of one type of half-metallic material, CrO_2.

MOKE was used to measure the magnetization hysteresis loops of CrO_2 and it was found that magnetization curves were similar to those measured by other techniques. MOKE was then employed to explore the in-plane anisotropy of the CrO_2 films. Finally, ultrafast pump-probe MOKE was used to probe the dynamics of the magnetization under fast excitation. Oscillations were seen which can be predicted by the Landau-Lifshitz equation. This thesis work shows the possibilities of using these optical techniques to study half-metallic materials.

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I. Introduction:

As computer technology becomes more sophisticated, high-tech industries need computers with larger storage capacity. Since they were first used as storage media, magnetic materials have increased the storage capacity of hard disks by several orders of magnitude. Today, we still stand several orders of magnitude below the atomic storage capacity limit. The current limit for the storage density is set by the sensitivity of magnetic sensors used to read the data. Another important concern for these devices is retrieval speed. It does no good to create a hard disk with several terabytes of information on it if it cannot be accessed in a timely manner. With these concerns in mind, research in magnetic materials is important if we are to continue to see large gains in storage capacity in hard drives.

Magnetic sensors used in hard drives today employ a property known as giant magnetoresistance (GMR). Giant magnetoresistance is a large change of the resistance due to application of a magnetic field. These materials are usually composed of layered magnetic and non-magnetic thin films whose different magnetic properties cause the observed changes in resistance. The amount of GMR depends on the amount of spin-polarization in the magnetic materials used. Spin polarization is defined as the ratio of current carried by the "up" and "down" spin electrons. There is a special class of ferromagnets, known as half-metallic materials, which are believed to be 100% spin polarized. Because half-metals are expected to show a very strong GMR effect, the bit size in a hypothetical hard drive can be made smaller, allowing more information to be stored per unit area. Producing, measuring and exploiting half-metallic behavior, however, has proven difficult.

In this thesis work we employ optical techniques, namely the Magneto-Optical Kerr Effect (MOKE) and ultrafast pump-probe MOKE to probe the behavior of one type of half-metal, CrO_2. MOKE was used to measure the magnetization hysteresis loops of CrO_2. It was found that the magnetization curves in this study were similar to those measured by other techniques. MOKE was then employed to explore the in-plane anisotropy of the CrO_2 films. Finally, ultrafast pump-probe MOKE was used to probe the dynamics of the magnetization under fast excitation. Oscillations were seen which can be described by the Landau-Lifshitz equation. This thesis work shows the possibilities of using these optical techniques to study half-metallic materials. Particularly, we can probe the ultimate time scale for flipping the magnetization in this material. For a high storage capacity device to be effective, it must be able to search, read, and write quickly. Thus knowing how long it takes for domains to switch is of the utmost importance.

II. Theory

A. Magnetism

The main types of magnetic materials are paramagnetic, diamagnetic, ferromagnetic and antiferromagnetic. Paramagnetic materials have no net magnetization in the absence of an external field. When a field is applied, the materials have an induced net magnetic moment because individual atoms experiencing a torque and moving such that their individual dipole moments are aligned parallel to the applied magnetic field.

Another type of magnetism is diamagnetism. This type of magnetism can be understood to be the result of electrons slowing down because of a change in the magnetic flux. This induced magnetization is antiparallel to the applied magnetic field.

CrO_2 is ferromagnetic, and thus this category is the one in which we are the most interested. Ferromagnetism is a quantum effect caused by the alignment of electron spins due to exchange coupling. Exchange coupling depends on the Pauli exclusion principle, which forbids electrons in the same space being in the same state. The spins align because the situation where the energy is minimized is the one where the spins align and are as far apart as possible. This minimizes the Coulomb repulsion, which is inversely proportional to the distance between electrons. Antiferromagnetism is similar to ferromagnetism in that there is exchange coupling, but alternate atomic layers align anti-parallel to each other, giving no net magnetization.

Heat can destroy the net magnetization of a material. By increasing the temperature above the point at which the influence of the thermal energy (tending to randomize the spins) overcomes the alignment (caused by exchange coupling). This temperature is known as the Curie temperature.

Another distinguishing characteristic of ferromagnets are domains, or groups of atoms with spins aligned. In a material that is not magnetized, these domains will point in different directions randomly (Figure 1a). [7] If a magnetic field is then applied, a single domain can exist parallel to that field. The strength of the field at which the single domain forms is called the saturation field. A more accurate picture can give better understanding of this process. Specifically, the direction of magnetization in the domains does not simply flip. The spins of the atoms near the edges near the domains close to parallel to the field influence the spins of the atoms adjacent to them. This causes the domains with magnetization close to parallel to the applied field to grow, while the others shrink (Figure 1b). At saturation, there is a single domain aligned with the applied

magnetic field (Figure 1c). When the field is then decreased, some atoms become randomly aligned, but the vast majority will remain aligned in the same direction (Figure 1d). This is called the residual magnetization, and it is exactly why ferromagnetic materials are useful when applied to the creation of memory storage devices.

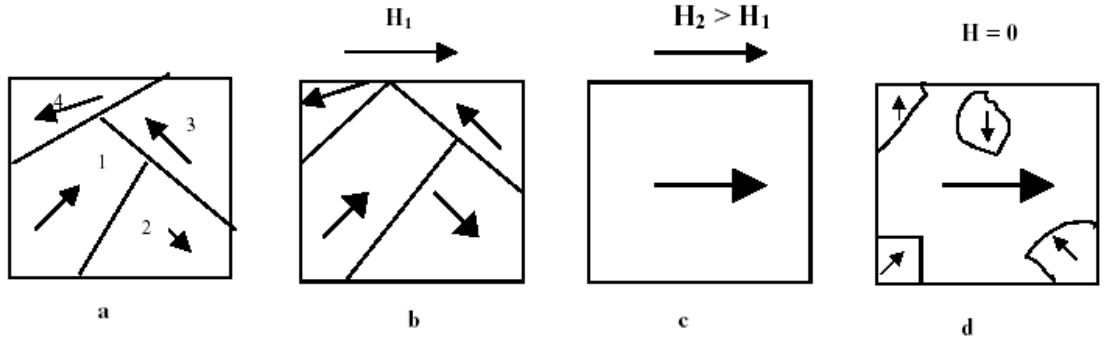

Figure 1: A simple diagram of the magnetization process in a ferromagnet. The bounds between domains are the domain walls, which disappear when the sample reaches saturation. H is the applied magnetic field. Taken from [7].

This also causes hysteresis. Hysteresis loops are created when the magnetization of the sample or some quantity that indicates that magnetization is plotted versus the magnetic field applied.

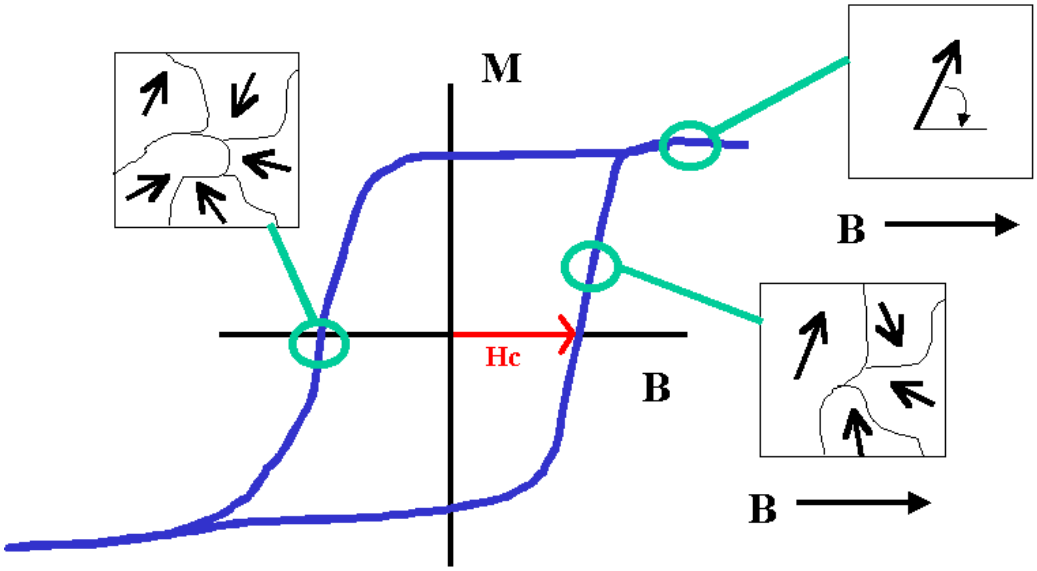

Figure 2: An example of a hysteresis loop. H is the applied magnetic field, and M is the magnetization of the sample. Hc is the coercivity.

B. Electron Band Structure Pertaining to Half Metals

Electrons in atoms fill shells with discrete energies in a specific order. They fill shells with the lowest energies first, and then continue to fill to minimize energy. In the most stable situation, the number of electrons in an atom is equal to the number of protons. This can leave some room in the shells for more electrons. When atoms are bonded by covalent bonds (where the atoms share electrons) there is a small problem. The electrons are shared between the atoms, and yet they have the same quantum numbers, which is forbidden by the Pauli exclusion principle. To compensate for this, when atoms are covalently bonded, the energy levels of the material split to compensate. When a large number of atoms are bonded, this leads to an equally large number of splits in the energy levels of the atoms and the formation of bands. Bands are considered to be a continuum of energy states that electrons can occupy. Different materials form different band structures, and thus have different properties. Specifically, the band structure of a material determines its conducting properties. When the bonding occurs, there are empty and full bands indicating available and unavailable states, respectively. In some materials, there is no gap between the filled and empty bands, and in others there are gaps of varying sizes. Electrons can travel from one atom to another in the empty bands, so when enough energy is added there can be a current that flows through a material. If there is no gap, only a small amount of energy needs to be added to create a current, so materials with no gap between empty and full bands are conductors. In insulators, there is a large gap and a large amount of energy is needed to create a current. There is a third class of materials with small to intermediate gaps called semiconductors.

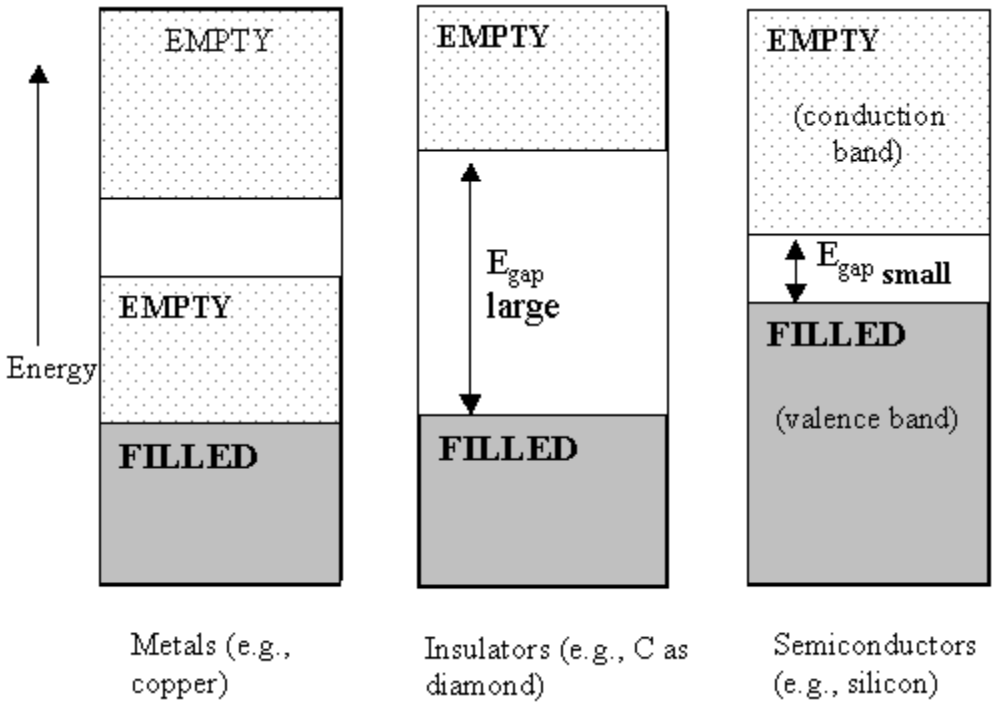

Figure 3: Band structure diagrams for metals, insulators, and semiconductors. In metals the empty and full levels are connected. In insulators, the empty and filled levels have a large gap between them. In semiconductors, there is a gap, but it is a small gap. The amount of energy needed for conduction depends on the size of the gap between the bands.

Half metals are materials that are conductors or insulators based on the spin of the electrons in the materials. When the spin of the electrons is up, the empty and full bands are connected, and the material is a conductor. When the spin is down, the bands are separated and the material is an insulator (Figure 3). This makes a half metallic material an ideal magnetoresistive material because it will result in a change in resistance that is extremely large.

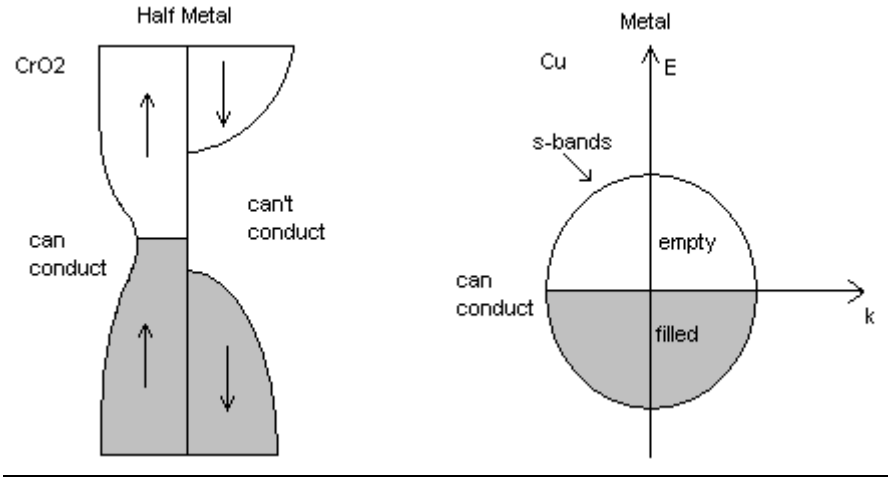

Figure 4: The band structure diagrams for half metals compared to that of a metal. The material is a conductor when the electron spin is up, and an insulator when the electron spin is down.

C. Magneto-Optical Kerr Effect (MOKE)

Magneto-Optical Kerr Effect (MOKE) is used to study the magnetic properties of materials. There are other methods that can accomplish this, including vibrating sample magnetometry, or VSM, and SQUID magnetometry, but MOKE is useful for studying the change in magnetization because any type of surface can be studied and a sample can be rotated or translated with ease. [7] MOKE is observed as a rotation of the polarization of light incident on a sample, and can give information about the magnetization of a sample indirectly.

There are three different types of MOKE experiments: polar, transverse, and longitudinal MOKE. Polar MOKE involves the magnetization perpendicular to the surface of a sample (see Figure 5a), transverse MOKE measures the magnetization perpendicular to the applied magnetic field and the plane of incidence (see Figure 5b), and longitudinal MOKE involves the magnetization of the sample in the direction of the plane of incidence and the applied magnetic filed (see Figure 5c). The longitudinal MOKE was used in this study.

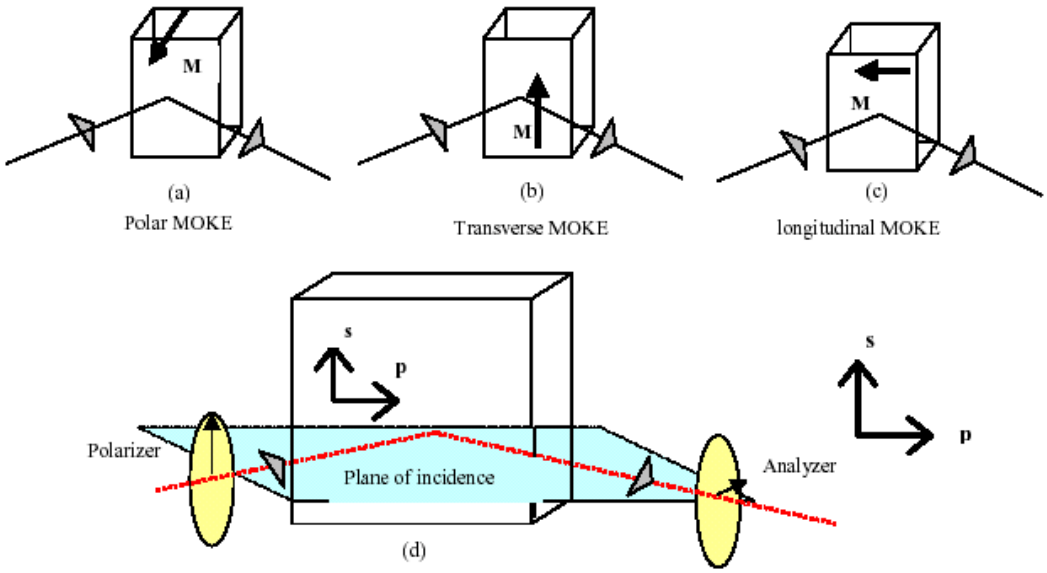

Figure 5: This diagram shows the linear MOKE setup. The laser beam travels as indicated by the arrows. The **s** and **p** directions are also shown in this figure. Taken from [7].

The **p** and **s** directions are defined relative to the plane of incidence (the plane in which the laser beam is shone), with **p** being parallel to the plane and **s** perpendicular to **p**. The Kerr effect is measured by passing the incident light through a polarizer and then the reflected light is passed through an analyzing polarizer, or analyzer (see Figure 5d).

The reflected electric field can be written $E_r = \mathbf{S}E_i$, where E_i is the incident electric field and **S** is the matrix:

$$S = \begin{pmatrix} r_{pp} & r_{ps} \\ r_{sp} & r_{ss} \end{pmatrix} \qquad (1)$$

The r's are called Fresnel coefficients and are proportional to the index of refraction and incident angle. [12]

The diagonal elements of the **S** matrix do not contribute in the longitudinal case, making the off-diagonal elements like r_{sp} important. Only materials with a net magnetization will gave off-diagonal components such as r_{sp}, and it is these components that result in the light rotation. The detected light is the component that passes through the crossed analyzer polarizer. Calculating the intensity, I (time averaged), it can be found:

$$I \propto \left| m_l^2 r_{ps}^2 \right|^2 I_o \qquad (2)$$

where m_l is the longitudinal magnetization [12].

D. Pump-Probe or Ultrafast MOKE

Information about the time or dynamical behavior of the magnetization can be found by using ultrafast lasers to do the MOKE experiment. In this type of experiment, a single ultrafast beam is split into two: a pump beam and a probe beam. The pump beam modifies the magnetization of the material (usually by raising the temperature), while the probe beam is used to detect MOKE. MOKE is measured as a function of time delay between the pump and the probe pulses. This gives us "snapshots" in time of how the magnetization relaxes after it has initially been modified or perturbed.

The Landau-Lifshitz equation is a differential equation that describes the motion of magnetic moments in a sample in an applied magnetic field over time.

When **I** is the magnetization vector, the Landau-Lifshitz equation has the form:

$$\frac{d\mathbf{I}}{dt} = -v(\mathbf{I}\times\mathbf{H}) - \frac{4\pi\mu_o\lambda}{I^2}(\mathbf{I}\times(\mathbf{I}\times\mathbf{H})) \qquad (1)$$

The term λ, called the relaxation frequency, has units of s^{-1} and determines the strength of the damping. The first term is explained by the idea that a magnetic field "feels" a torque in the presence of a magnetic field. The second term is a damping term, allowing for the direction of the dipole to come parallel to the applied magnetic field. [11]

This equation can also be written as follows:

$$\frac{d\mathbf{I}}{dt} = -v(\mathbf{I}\times\mathbf{H}) + 4\pi\mu_o\lambda\left\{\mathbf{H} - \frac{((\mathbf{I}\cdot\mathbf{H})\mathbf{I})}{I^2}\right\} \qquad (2)$$

This equation can be shown to be equal to the exact equation of motion:

$$\frac{d\mathbf{I}}{dt} = -v\left\{\mathbf{I}\times\left(\mathbf{H} - \frac{\alpha}{vI}\frac{d\mathbf{I}}{dt}\right)\right\} \quad (3)$$

where

$$\frac{4\pi\mu_o\lambda}{vI} = \alpha \quad (4)$$

Damping simplification:

In this treatment, we will consider only the case where $\alpha^2 << 1$, which is the undamped case. H includes not only an applied magnetic field, but also an effective field due to, for example, anisotropy. We will assume that **H** is in the –z direction. In this case, the equation of motion becomes

$$\frac{d\mathbf{I}}{dt} = -\nu(\mathbf{I} \times \mathbf{H}) \qquad (5)$$

If we write this in Cartesian coordinates, we get

$$\frac{d\mathbf{I}}{dt} = -\nu \det \begin{pmatrix} \mathbf{x} & \mathbf{y} & \mathbf{z} \\ I_x & I_y & I_z \\ 0 & 0 & -H \end{pmatrix} = \nu I_y H \mathbf{x} - \nu I_y H \mathbf{y} + 0 \qquad (6)$$

or

$$\begin{aligned} \frac{dI_x}{dt} &= \nu I_y H \\ \frac{dI_y}{dt} &= -\nu I_x H \\ \frac{dI_z}{dx} &= 0 \end{aligned} \qquad (7)$$

To solve the equation, we must first separate the variables:

$$\begin{aligned} I_x &= \frac{-1}{\nu H}\frac{dI_y}{dt} \\ I_y &= \frac{1}{\frac{\nu H}{dt}}\frac{dI_x}{dt} \\ 0 &= \frac{dI_z}{dx} \end{aligned} \qquad (8)$$

$$\begin{aligned} \frac{d^2 I_x}{dt^2} &= -\nu^2 H^2 I_x \\ \frac{d^2 I_y}{dt^2} &= \nu^2 H^2 I_y \\ \frac{dI_z}{dx} &= 0 \end{aligned} \qquad (9)$$

Solving these equations we have

$$\begin{aligned} I_x &= I_s \sin\theta_o e^{iw_{ot}} \\ I_y &= I_s \sin\theta_o e^{iw_{ot}+i\pi/2} \\ I_z &= I_s \cos\theta_o \end{aligned} \qquad (10)$$

Where $w_o = \nu H$, and ν is a gyromagnetic constant given in [11].

This means that the magnetization precesses with a fixed angle θ_o from the z-axis. If we were to detect one component of the magnetization (such as the x component, as we do in longitudinal MOKE), we would see that the magnetization oscillates in time.

In a sample with a uniform magnetization, it is difficult to perturb the magnetization enough to see these oscillations. But in a sample with a naturally preferred direction for the magnetization (anisotropy), we can attempt to pull the magnetization away from its preferred direction (the easy axis) and then watch the sample precess and relax back to its natural state. One way to due this is to apply a magnetic field perpendicular to the easy axis and randomize the magnetization with an ultrafast laser pulse. Then the relaxation back to the easy axis can be observed with MOKE. This type of ultrafast measurement will be discussed later. Due to anisotropy in the sample, the effective magnetic field in the sample is changed. The anisotropic field in the sample is a preferred direction of magnetization caused by the orientation of its atoms in the crystal, or the "pinning" effect of a nearby layer in a multilayer film.

III. Experiment

A. Samples

Two types of samples were studied in this work. First a FeMn/Co exchange-biased wedge was used to test our MOKE setup in preparation to study CrO_2. The FeMn/Co wedge samples studied as a test case in this project were made by sputtering in Dr. William Egelhoff's lab at the National Institute of Standards and Technology in Maryland. The antiferromagnetic layer was of constant thickness, while the ferromagnetic layer was grown as a wedge of varying thickness. The sample was heated after deposition and then cooled in the presence of a magnetic field to impart an exchange biasing (pinning) in a desired direction. The thickness of the ferromagnetic layer varied linearly. We took MOKE data at various points along the wedge, and then plotted

exchange biasing as a function of inverse thickness. This gave us insight into how exchange biasing depends on the thickness of the ferromagnetic layer.

The CrO_2 thin films were also made in Dr. Egelhoff's lab at NIST by heating Cr_2O_3 in an oxygen rich environment. The films were grown on TiO_2 substrates. The TiO2 substrate is placed in a small aluminum foil box, and then the Cr2O3 powder is poured in. The samples were then placed in an oven and heated to ~ 450 K in an overpressure of O2 for ~ 45 minutes. After that time, the sample is removed and is cooled when its receptacle is plunged into water. The sample is then tested for quality by a check of its magnetic properties and resistance. If the sample is attracted to a magnet, and if its resistance is small, then it is considered a "good" CrO2 sample. CrO2 is the only possible material made from chromium and oxygen in that temperature and pressure range that is both conducting and ferromagnetic. Because the CrO2 films are grown on a TiO2 crystal, they are considered to be essentially a single crystal. Others have grown single crystal CrO2 films, but Dr. Egelhoff's lab is the only one of which we are we are aware that grows these crystals in this way. Other labs use chemical vapor deposition (CVD) to grow the films. One reason to use MOKE to study these films is to be sure that they really are good films. By comparing the MOKE data to data obtained in other studies, we should be able to tell if the samples are indeed good samples.

B. MOKE

As mentioned in section II-C, in MOKE the polarization of an incident light beam is rotated upon reflection from a magnetized sample. In the MOKE experiment, the reflected light is detected by an analyzer that is crossed relative to the first polarizer (see

Figure 5). In our experiment, a 5 mW diode laser or an amplified ultrafast Ti:Sapphire (Spectra-Physics) laser was used as the light source. The beam was modulated by an optical chopper (Stanford Research Systems) and the light measured on a silicon diode by lock-in detection .The samples were placed in an electromagnet and the MOKE signal measured as a function of applied field, giving hysteresis loops.

The FeMn/Co samples we first studied were "pinned" layers, so there is a preferred direction of magnetization, causing a shift in the hysteresis loop. The amount that the loop is shifted is known as the exchange bias. We studied the strength of the exchange biasing as a function of Co thickness. The FeMn/Co system was a test system being used to learn more about MOKE and the ultrafast MOKE, to prepare for the difficult experiment of detecting MOKE on CrO_2 (because the Kerr rotation is relatively small).

The MOKE hysteresis loops from CrO_2 thin films were then measured. First we compared the MOKE curves to magnetization measured with other techniques such as SQUID magnetometry and found they were similar. Then we measured the MOKE curves as a function of the angle of the applied magnetic field to the easy axis, to explore the natural anisotropy present in CrO_2 films. The samples were rotated in the applied field using a rotating optical mount.

Another measurement technique we explored in this thesis work was ultrafast MOKE. This experiment allowed us to determine how long it takes for the magnetization of given domains in CrO_2 to change. This is of interest to people working in industry, because read/write heads in a hard disk cannot retrieve or write data faster than the time takes for the domains to switch their magnetization.

We used ultrafast MOKE to measure how long it takes for the atoms in our magnetic samples to align their dipole moments. In some setups, a pulse, known as the pump beam, is shone on the sample. The purpose of this beam is to excite the electrons in the sample and heat the electrons above the Curie temperature, causing the domains to switch and destroy their alignment. This is done in an applied magnetic field, so after the pump pulse, the domains begin to realign themselves with the magnetic field. At some time interval after the pump beam a beam known as the probe beam is shone on the sample. This beam allows us to measure either reflection or MOKE through the same method as the longitudinal MOKE setup (see Figure 5), which gives us information about the magnetization of the sample. Sending the probe beam through a "delay line" lengthens the path, can change the time interval between these two pulses (see diagram in Figure 6). This gives a picture of how the material behaves as a function of time.

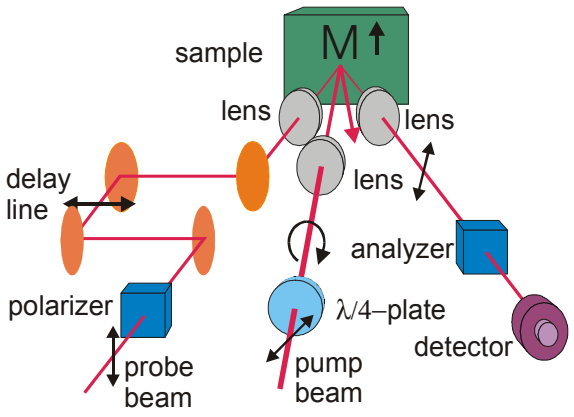

Figure 6- Pump-probe ultrafast laser experiment where reflection of the probe is monitored. With the use of a polarizer and analyzer, the MOKE response can be measured. The ultrafast laser had pulses ~150 fs long, with a repetition rate of 1 kHz and a wavelength of 800nm. Taken from [6].

IV. Results

A. Linear MOKE on FeMn/Co

First we studied the strength of the exchange biasing as a function of Co thickness in FeMn/Co wedges.

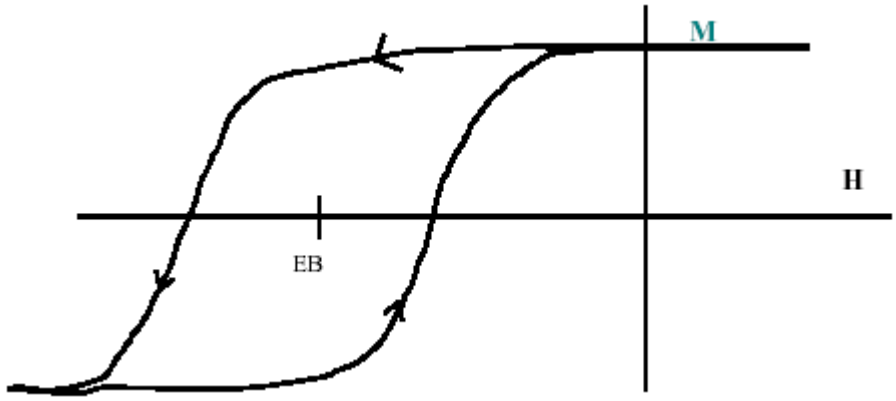

Figure 7: This hysteresis loop is labeled to show exchange bias. The amount the center of the loop is shifted is the exchange bias. In most samples, the exchange bias is negative. Taken from [7].

Figure 7 shows a plot of the exchange bias (EB) in Oersteds versus 1/thickness for the Co layer. According to the theory of Mazelomoff [13], we expect the EB to be inversely proportional to thickness (because EB is an interfacial effect between the antiferromagnetic and ferromagnetic layers). Our data show this dependence and they also agree with previous data collected from these samples (see Figure 8). Data was collected at 3 mm intervals down two samples. The two data runs shown above were taken on two wedges with different thickness ranges for the Co. The samples were both FeMn/Co wedges. The error in the measurement has been previously measured, and the error bars are less than the size of the symbols on the graph. The error is mainly caused by the change in thickness of the sample and the 1 mm spot resolution of the beam translates into 5 angstroms thickness uncertainty. Also, there is error inherent in the measurement of H_{EB} and H_C. [7] We believe that the offset of the two lines is an artifact

of the wedges. Different wedges give different data for this experiment. The reasons for this are not entirely clear, but we believe that the domains in the different wedges change magnetization differently because the wedges are each of a different thickness range.

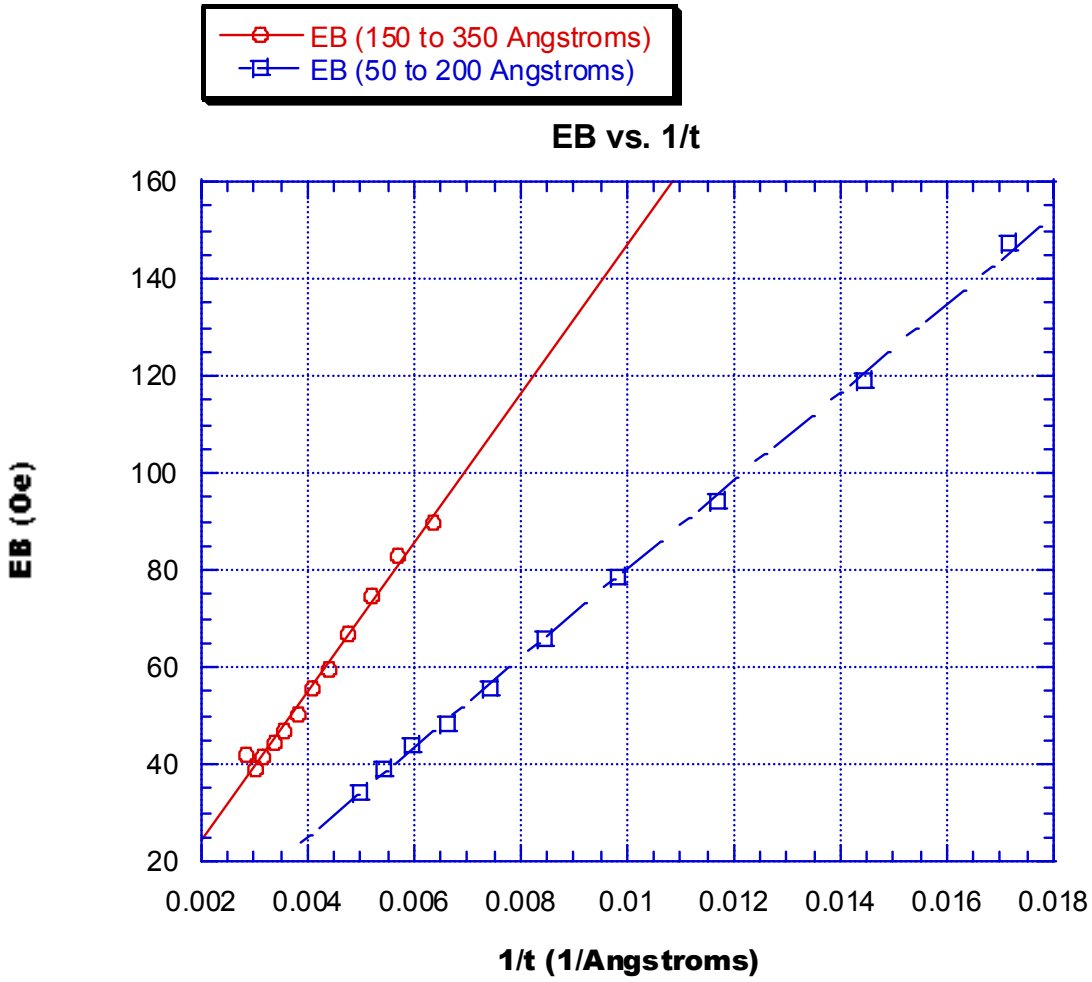

Figure 8: This graph shows electron bias in Oe vs. 1/t where t is the thickness of the FeMn/Co samples in nm.

Figure 9 are hysteresis loops created using linear MOKE. We successfully obtained MOKE curves for CrO_2, which will allow us to study the magnetization using this technique. Our curves are similar to those obtained by other methods such as SQUID magnetometry.

One experiment we attempted was to explore the natural anisotropy of the CrO_2 by measuring the MOKE curves as a function of the angle of the applied field to the easy axis. Some of the MOKE curves are shown below in Figure 9. The angle θ is defined is the angle between the easy axis of the film and the applied magnetic. Also shown is a graph of the coercivity of the samples (see Figure 10). Some type of symmetry is seen, and there is a definite easy and hard axis. We could not fully explore the angular dependence, however, because our electromagnet was limited in field and we could not saturate the magnetization for angles greater than ~ 60^o.

B. Linear MOKE on CrO_2

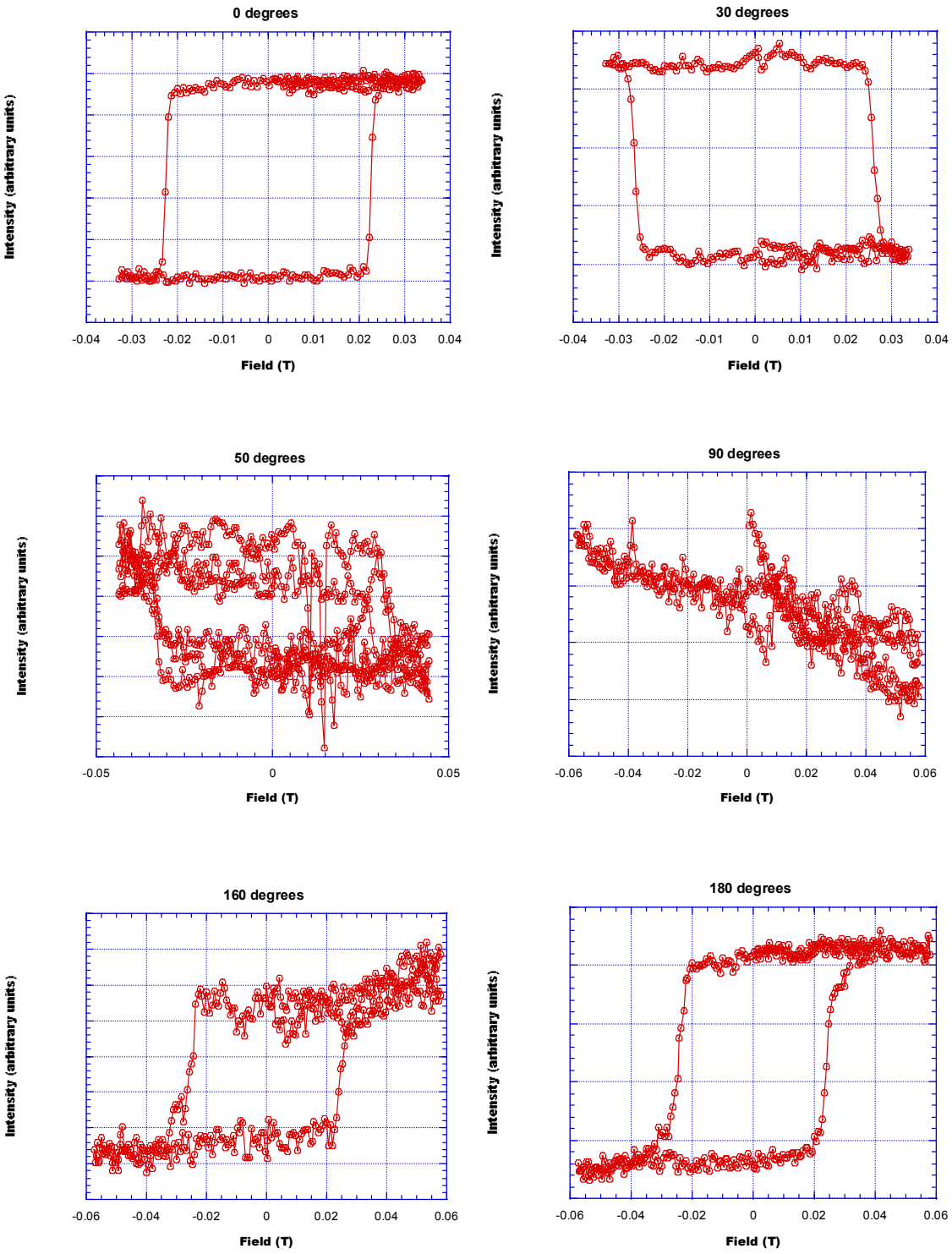

Figure 9: These hysteresis loops are the result of the linear MOKE measurements taken while rotating the sample periodically. The magnetization is plotted along the y-axis, while the applied magnetic field is plotted along the x-axis.

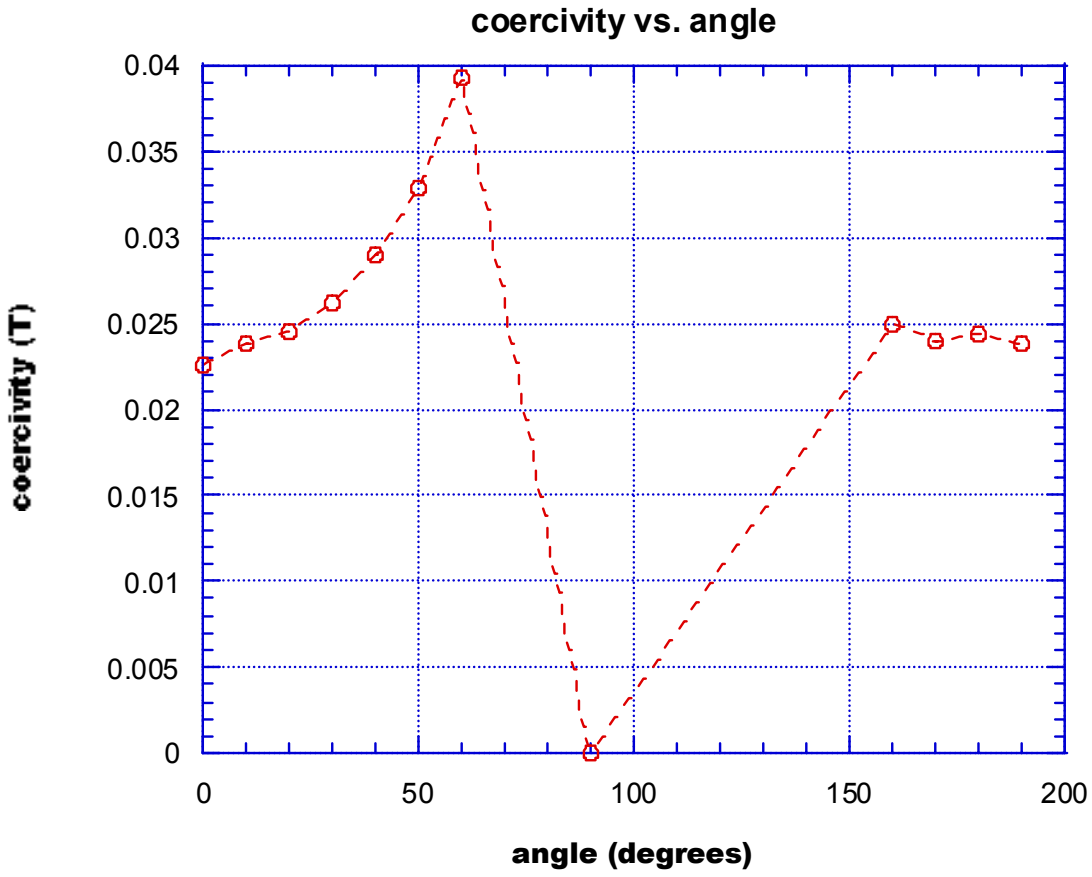

Figure 10: The coercivity changed with the angle. It is at it's lowest points at 0 and 180 degrees, and raises toward where the hard axis at 90 degrees.

The graph in Figure 10 was created by calculating the coercivity from the hysteresis loops as a function of the angle through which the sample is rotated. As the magnetization being measured gets closer to being aligned with the hard axis, it becomes more difficult to flip the direction of the domains. This requires a greater applied field, and the data in the middle of the plot is missing because the magnet used in this experiment could not be safely operated with sufficient fields. However, there is enough

data to state that the coercivity is symmetric about the hard axis (90°). Yang et. al. saw a similar effect using VSM. [9]

C. Ultrafast MOKE on CrO_2

We measured pump-probe ultrafast MOKE as a function of the angle of the applied field relative to the hard axis. Again, as discussed in the theory section, we expect that for the field aligned with the hard axis the pump pulse will initiate precession in the magnetization that will be detected in our longitudinal MOKE setup. Conversely, when the sample's easy axis is aligned with the applied field no precession or oscillations will be seen. We see evidence for this, as shown in Figure 11.

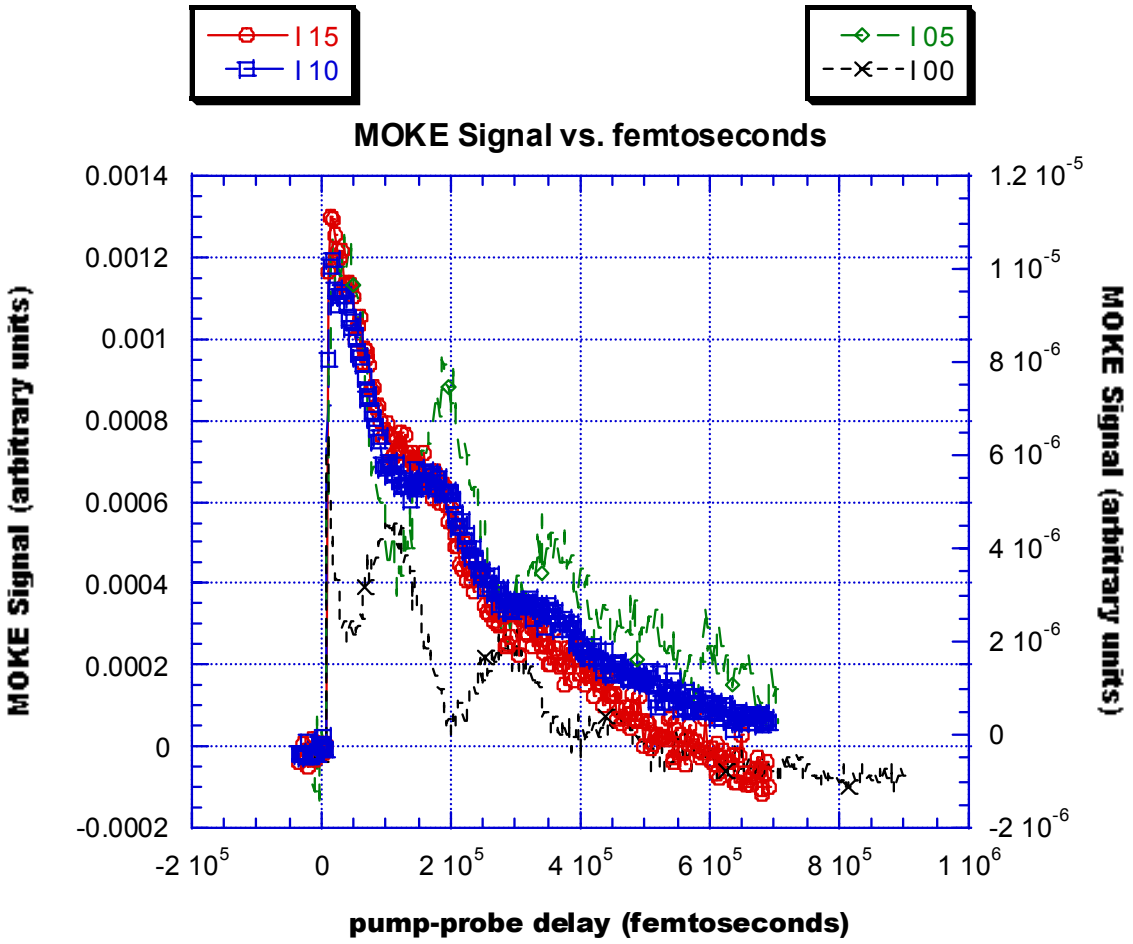

Figure 11: This graph displays the different MOKE signals vs. time delay between the probe beam and the pump beam in femtoseconds. This is a double axis graph, due to the fact that the signals are so dramatically different. I 00 refers to the hard axis, defined to be 0^{o}. I 05 refers to 5^{o} from the hard axis, I 10 to 10^{o} from the hard axis, and I15 to 15^{o} from the hard axis. The x-axis should be labeled Pump-probe delay (femtoseconds). The y-axis can be called MOKE signal (arbitrary units). This data was taken by Hailong Huang.

The portion of the data in the negative time region corresponds to an area where the probe beam arrives before the pump beam. This is why there is no signal in that region. The precession of the magnetization in the sample causes the oscillation in the data. This is precisely what we expected to see based on our study of the Landau-Lifshitz equations. There is also decay in the signal, caused by the torque on the dipoles that

brings them into line with the applied magnetic field. This is also what we expected. The damping term we eliminated from the Landau-Lifshitz equation gives rise to this effect. The period of the oscillations is ~ fs (estimate peak to peak on graph). The oscillations seen are similar to those of Zhang et. al. in CrO_2. [14]

V. Conclusion and Future Work

MOKE can give valuable information about magnetic materials. We have successfully detected MOKE from CrO_2 and have measured hysteresis loops. We have detected the anisotropy expected in this material. We have conducted initial ultrafast pump-probe experiments and show that they can be useful for learning about the time dependence of magnetization processes in the important half-metal CrO_2.

There is a slight problem with the ultrafast MOKE setup: the materials we wish to study need the pump to heat the electrons above the Curie temperature (for nickel, the temperature is approximately 700 K). To solve this problem, we hope to make a device that will change the magnetization of our sample in another way. We will use the pump beam discussed above to trigger a fast photodiode or to strike a GaAs wafer, making an electrical connection and applying a voltage on a ring of wire etched into a circuit board. The current caused by this voltage will create a magnetic field (we can easily measure, calculate, and calibrate the system). We can then probe the sample at different time intervals and see how the magnetization changes as a function of time. We feel that this method is preferable to other methods as it is less destructive and invasive for our

samples. This method has also been used with some success by other researchers, and appears promising. [10]

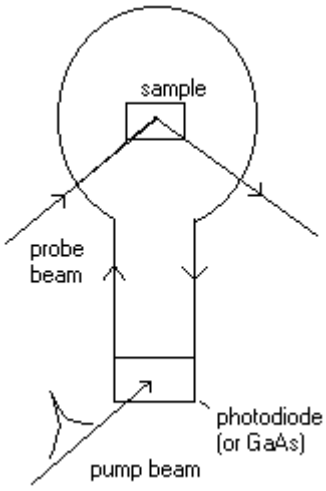

Figure 11- An alternative to the pump-probe ultrafast laser experiment. The pump beam hits a photodiode, triggering a current in the ring, which has the sample fixed in the center. A magnetic field will be applied to the sample. The probe beam operates as in the pump-probe method.

VI. References and Related Information:

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