Rotational Study of the Thermal Dependence of the Exchange Bias Property of Magnetic Thin Films by the Magneto-Optical Kerr Effect (MOKE)

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

by

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Abstract

The main focus of this research was to conduct a systematic study of the thermal dependence of the exchange bias interaction that is present in magnetic multilayered thin films consisting of adjacent ferromagnetic (F) and antiferromagnetic (AF). The main difference between this research and previous studies is that this research details a complete rotational study of magnetic thin films combined with a systematic temperature study of the exchange bias properties of the samples. An IrMn/120ÅCo magnetic thin film sample (where IrMn is the AF material and Co is the F material) was studied by the Magneto-Optic Kerr Effect (MOKE). The sample was heated and cooled in the presence of a magnetic field to 11 different temperature settings, ranging from room temperature to 245.5^{o}C. We found that the exchange biasing interaction became manifest with relatively little heating, and began to saturate at higher temperatures with behavior that had been seen in other systems. The magnetic anisotropy, determined by measuring the magnetic properties as a function of angle between the exchange bias axis and the applied magnetic field, did not show a simple evolution to uniaxial (single-axis) anisotropy as expected. The data though did show a general trend towards thermal activation based on thermal probability.

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Acknowledgments

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I. Introduction

The main focus of this research was to conduct a systematic study of the thermal dependence of the exchange bias interaction that is present in magnetic multilayered thin films consisting of adjacent ferromagnetic (F) and antiferromagnetic (AF) layers.[1,2] The exchange bias interaction between the AF and F layers causes the magnetization of the F layer to become "pinned" along a certain axis, making it difficult to rotate.[1] This leads to a shift in the hysteresis loop.[2] This exchange bias interaction is an important part of magnetic thin films used for magnetic sensing technology.[3]

The study of magnetic multilayered thin films is of great importance to the modern electronics industry and general technological progress. For example, since the introduction of magnetic multilayered thin films as sensors in commercial hard drives in the 1990s, the storage capacity of PC hard drives has increased rapidly.[3] This progress would, most likely, not have been possible without these magnetic materials.

In this research, an IrMn/120ÅCo magnetic thin film sample (where IrMn is the AF materials and Co is the F material) was studied in order to further understand the origin and nature of the exchange-biasing, and to study its affect on the magnetic anisotropy of the thin film. We undertook a detailed study of magnetic anisotropy as induced by exchange biasing, and its dependence on the temperature to which the film was subjected. We found that the exchange biasing interaction became manifest with relatively little heating, and began to saturate at higher temperatures with behavior that had been seen in other systems.[4] The magnetic anisotropy, determined by measuring the magnetic properties as a function of angle between the exchange bias axis and the applied magnetic field,[5],[6] did not show a simple evolution to uniaxial (single-axis) anisotropy as expected. The main difference between this research and previous studies[7,8,9,10,11] is that this research details a complete rotational study of magnetic thin films combined with a systematic temperature study of the exchange bias properties of the sample.

II. Basic Magnetic Theory and Definitions

II a) Types of Magnetism

At its basic level, magnetism is caused by the movement of electrons around their core atomic nuclei (orbital angular momentum) and the rotation of the electrons around their own axes (spin).[12] These electron movements result in magnetic moments which determine the magnetic properties of the system in which they reside.[13] If the resulting orbital moments, when exposed to an applied magnetic field, align against the applied field then the material is termed diamagnetic and it exhibits diamagnetism, meaning that the system can not be permanently magnetized.[13] Paramagnetism is the opposite case, where the resulting orbital and spin moments of the system, when exposed to an applied external magnetic field, will line up parallel to the applied external magnetic field.[12] Further, ferromagnetism can be thought of as an extension of paramagnetism, in that after exposure to an applied external field, the system retains its magnetic alignment and properties, whereas in paramagnetic systems magnetic properties are lost after the applied external field is removed.[13] Antiferromagnetism interestingly is a combination of ferromagnetism and diamagnetism.[5] Locally, an antiferromagnetism system is diamagnetic in that the magnetic moments are paired antiparallel to each other, but the system overall still has paramagnetic properties.[5]

The above definitions of basic magnetic properties are not absolute in that they are temperature dependent.[13] At 0 K, thermal fluctuations in a magnetic system are nonexistent and the coupling forces, which hold the magnetic moments together in their specified alignment, are at their strongest.[13] As the temperature increases, the thermal fluctuations of the system increase and interfere with the magnetic coupling between moments.[13] At a critical temperature, the thermal fluctuations have enough energy to completely disrupt the system's magnetic moment coupling.[13] At temperatures greater than this critical temperature, the system will act as a paramagnetic system.[13] For ferromagnetic systems this critical temperature is called the Curie temperature, whereas in antiferromagnetic systems it is referred to as the Néel temperature.[13] Concerning this research the Curie temperature of Co is 1400 K[14] and the Néel temperature of IrMn is 520 K.[15]

II b) Ferromagnetic Hysteresis

A fundamental property of ferromagnetic materials is hysteresis, or magnetic memory.[16] It is manifested by measuring the total magnetization of the sample versus the applied magnetic field.[16] For this thesis work, this was done using a Magneto-Optic Kerr Effect (MOKE) setup, which is described in detail in the next section. Hysteresis loops are formed when a system is magnetized and the system magnetic field "lags" behind the applied field and the two become out of phase.[16,13] This forms the familiar looking "S" shaped loop, that is commonly shown for magnetics. What happens is that if the sample is fully magnetized in one direction and the applied field begins at the sample's magnetization strength but is applied in an opposing direction, some of the magnetic domains of the system, which are collections of many magnetic moments[12], will be aligned in an opposing direction to the applied field.[13] When the applied field is reduced and then reaches zero, some of the magnetic domains will still be partially aligned in their original orientation.[13] This will leave a residual magnetization which is termed the remanence, meaning that the system will remain magnetized in the absence of an external field.[13] If you continue to apply the magnetic field in its current direction, then a negative field is recorded and finally the sample will be in its original situation except that the orientation of its system domains will be in the opposite direction.[13] If the applied field direction is then switched and its magnitude increased, the sample will realign its domains forming the bottom half of the hysteresis loop, with a different remanence point.[12] A sketch of a hysteresis loop and these domain processes are shown in Figure 1.

One important term relevant to the research conducted here and related to hysteresis loops is coercivity.[16] The coercivity (H_c) of the hysteresis loop is a measure of how much of a reverse applied magnetic field is required to reduce the magnetic field within the system to zero.[17] On a graph of a hysteresis loop, the coercivity is the distance along the applied field axis, where the magnetization of the sample is zero, from the origin to the loop.[17] The “S” shape of the hysteresis loop can be explained in terms of the coercivity.[13] Following the previous description, as the applied field is oriented in the opposite direction of the system and is reduced in magnitude, the domains that are aligned with the applied field will grow in preference to those that are not aligned with the applied field.[13] This will lead to very few large domains that are oriented with the applied field at the saturation end point.[13] When the applied field is then reversed for the bottom leg of the hysteresis loop, the very few large magnetic domains will reduce in size, as other domains that now align with the applied field are given preference.[13] These preferenced domains will now grow into larger domains and occupy most of the sample magnetic system domain space.[13] In the middle of each of these upper and lower legs of the hysteresis loop is a mixture of domains aligned in a multitude of different directions.[13] These middle points define the coercivity of the system.[12]

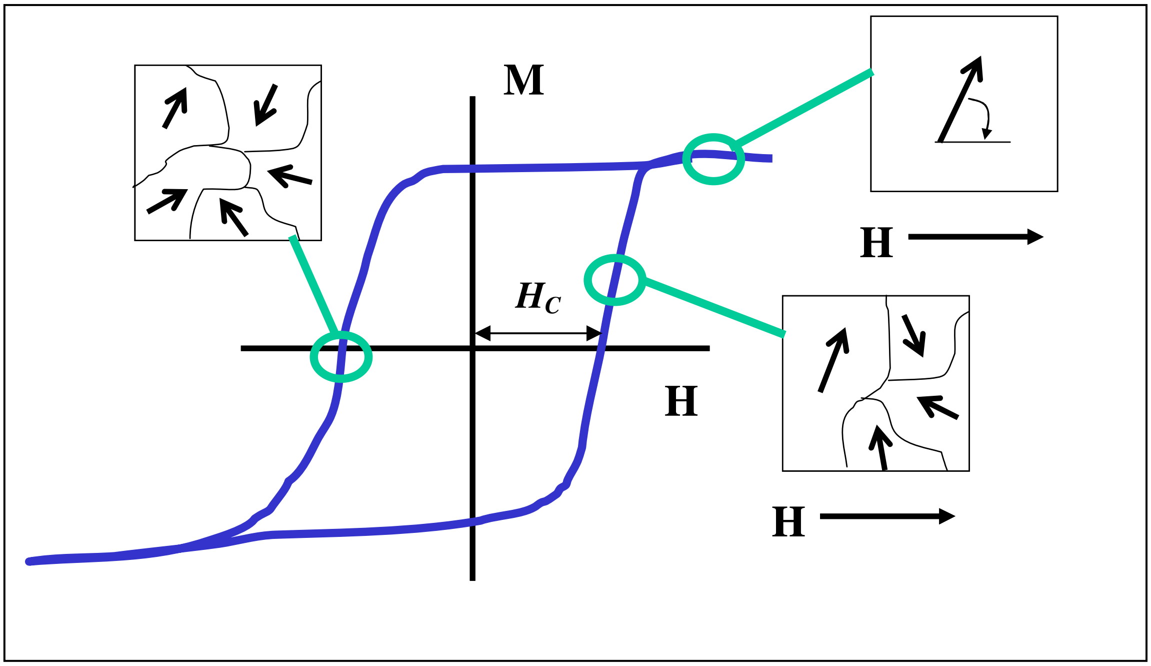


Figure 1 – Magnetization of domain spins in a hysteresis loop during the magnetization process[18]

III c) Exchange Biasing and Anisotropy

Exchange biasing arises when an antiferromagnetic thin film and a ferromagnetic thin film are in atomic contact and their magnetic domain electron spins interact at the interface between the two films.[1] Normally, the domain spins of the two systems would not necessarily react with each other, but when an AF/F exchange bias thin film is heated, in an applied magnetic field, beyond the Néel temperature of the AF material and below the Curie temperature of the F material, the F material's electron spins will align with the applied field and the AF material's electron spins will become randomly aligned. When the thin film is then cooled below the Néel temperature of the AF, in the presence of the applied magnetic field, the AF material's electron spins will be "pinned" in the direction of the F material's magnetization producing an uniaxial, unidirectional anisotropy, or preference of domain alignment.[1] This anisotropy tends to decrease with increasing temperature, and near the Curie temperature material systems tend towards isotropic behavior.[19] Also, this pinning process creates a shift in the hysteresis loop of the sample.[20] Instead of being centered on the origin, the hysteresis loop will be shifted either left or right.[20] The exchange bias field (H_{eb}) is taken as a measure of the strength of the exchange bias interaction.[2] It is the amount of shift of the center of the hysteresis loop from zero, as shown in Figure 2.[1]

The exchange bias interaction is very sensitive to sample parameters such as the thickness of the F and AF layer, as well as the grain size and morphology in polycrystalline samples.[20] The exchange bias interaction is set in materials, as mentioned, using increased temperature.[1] With increasing temperature, the exchange biasing interaction increases as more AF grains "activate."[21]

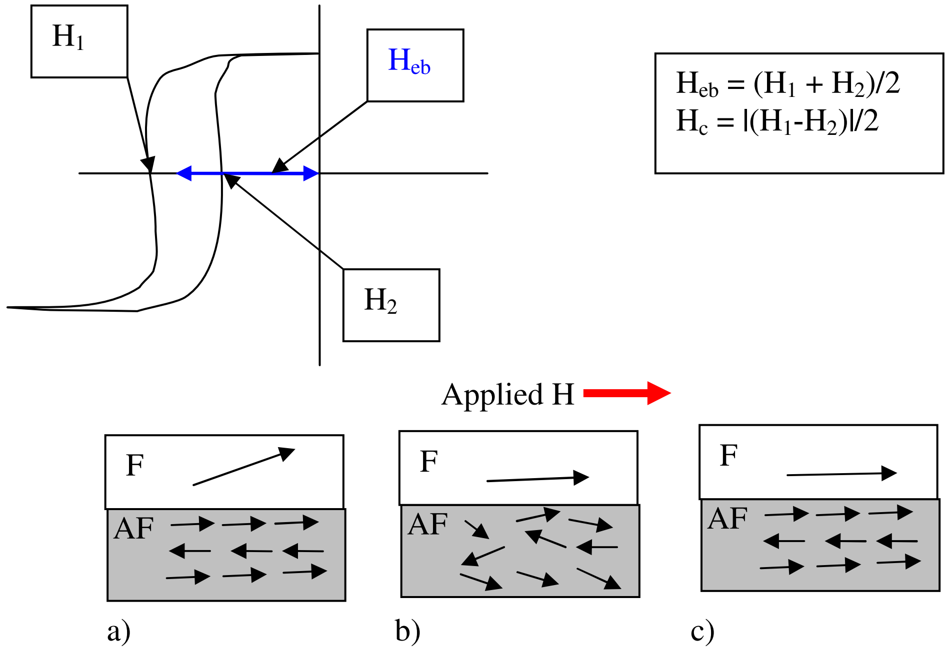


Figure 2 – Top: A hysteresis loop for an exchange biased bilayer, showing a shift from zero.

Bottom: A cartoon showing the setting the exchange bias interaction (pinning). a) The sample, when grown, has a random orientation of magnetization in the F layer. b) When the sample is heated close to the blocking or Neel temperature, spins in AF grains become disordered near the interface. An applied magnetic field sets the direction of the F magnetization. c) Upon cooling, the AF reorders, setting the exchange bias interaction at the interface (pinning).[22]

The coercivity (H_c) and the exchange bias field of a magnetic system are important in characterizing its behavior. For this research, one of the main things is the classification of the hysteresis loops obtained as either hard or easy axes. Easy axes are the energetically favorable anisotropic orientations for domains in magnetic systems.[19,6] If the applied external field is aligned parallel with an easy axis of the system, then the coercivity will be large.[6] Conversely, if the applied external field is aligned off the preferred, or easy axis, then the domains will be in an unfavorable orientation and will be in what is then termed a hard axis.[6] The coercivity for this type of axis is small.[6] The stereotypical example of a hard axis is a diagonal line.[6] Concerning the exchange bias, the further the hysteresis loop is shifted from the origin is an indication of how much energy is contained in the spin disorder and spin interactions at the interface between the AF and F layers of the magnetic system and in what direction the exchange bias is anisotropically oriented.[1] The study of the exchange bias is important because it is assumed that the hysteretic processes are taking place in the AF material.[21]

It is known that the exchange bias interaction can be induced in an AF/F bilayer thin film simply by growing the two materials together in an applied magnetic field.[1] However, larger values of H_{eb} are obtained by heating the thin film and cooling it in an applied magnetic field.[1] The temperature dependence of the onset of exchange bias has been well studied for many material systems.[4] In general, H_{eb} increases and then saturates as the sample temperature is raised and then cooled from what is known as the blocking temperature, which is typically less than the Néel temperature for the AF.[23] The blocking temperature is also the temperature at which the exchange bias tends to zero and the coercivity of the biased layer falls to that of the free layer as the sample temperature is raised.[23] For IrMn, the blocking temperature is approximately at the Néel temperature of 550 K.[23]

III. Experiment

III a) Sample

The sample studied was grown by magnetron sputtering in a vacuum chamber by the group of Dr. William Egelhoff at the National Institute of Standards and Technology. The sample was deposited on a silicon substrate and consisted of 5 nm of W, 5 nm of Cu, 10 nm of IrMn, 12 nm of Co, capped with 2.5 nm of Al_2O_3 to prevent oxidation. To study the onset of the exchange bias interaction, any residual exchange-bias interaction was effectively "erased' by heating the sample to 250 ^{o}C and cooling it while spinning the sample in an applied magnetic field.

III b) Magneto-Optic Kerr Effect Measurements [24]

The hysteresis loops were measured by making use of the magneto optical Kerr effect, or MOKE. When polarized light is transmitted on a magnetic surface, the reflected light is slightly rotated.[25] This is the Kerr Effect.[25] It arises due to the spin-orbit interaction between the electrical field of the incident light and the electron spins of the magnetic material.[26] The level of the spin-orbit interaction between the two mediums though is dependent on the strength of the applied magnetic field.[26] If the field is increased, the light is rotated more, and if the field is decreased, the light is rotated less.[26] This is the basic reasoning why a polarizer/analyzer setup is needed for these measurements. The polarizer polarizes the coherent laser light in one direction before it interacts with the magnetic thin film surface. The two mediums' spins couple, rotating the reflected laser light a small amount, typically on the order of a tenth of a degree.[25] The reflected laser light then passes through the analyzer, which is just another polarizer, set at about 90^{o} from the original polarizer. The diode detector then detects the intensity of the incoming light based on how much of the rotated light makes it through the analyzer. The basic equation for the intensity of light through a polarizer is:

$$I = I_o \cos^2 \theta \qquad (1)$$ [27]

Where I_o is the original intensity of the light, I is the intensity of the light after transmission thorough the polarizer, and θ is the angle between the polarized direction of the light after rotation from the Kerr effect and the transmission axis of the polarizer.[27] This process is shown in Figure 3.

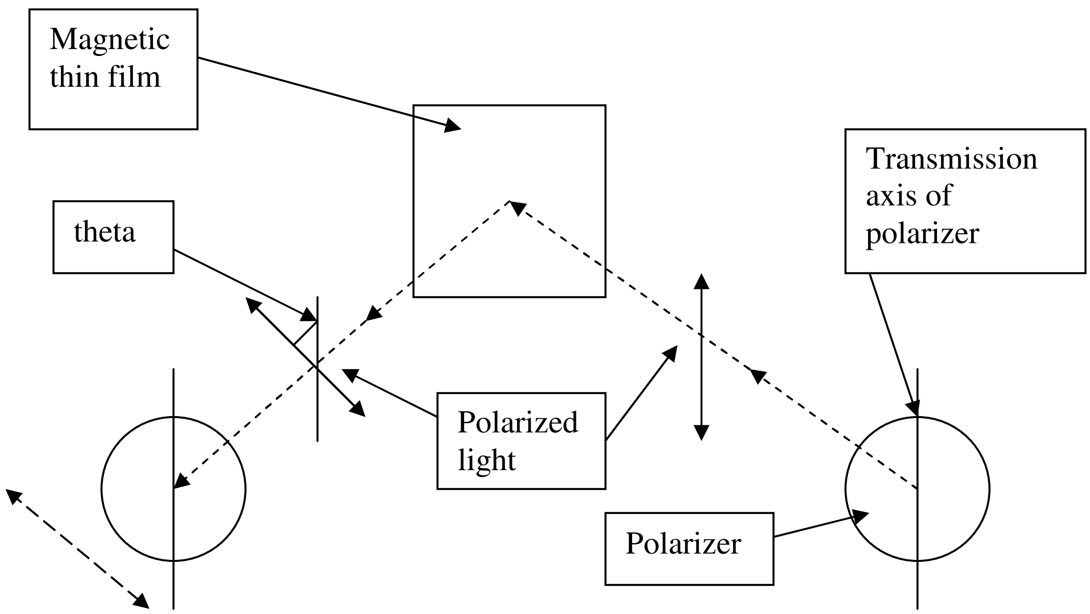


Figure 3 – MOKE Process. Light enters from the right polarized up/down. The light is then reflected off a magnetic thin film and is rotated by theta. The rotated light then transmits through the analyzer and is read by the detector at a reduced intensity.

Therefore, the analyzer is sensitive to the amount of rotated light. Since the rotation of the light is dependent on the strength and direction of the applied magnetic field,[26] then the hysteresis loop of the magnetic thin film to be studied here can be produced by varying the magnetic field in strength and direction and plotting out the obtained readings.

In our studies, the thin film sample was attached to the face of a rotatable mount, with a complete 360^o degree rotation of freedom marked off in 2^o degree increments on its face. The face of the rotatable mount was then centered between Helmholtz coils of an electromagnet, to provide the applied magnetic field. The coils were connected to a bipolar amplified power supply. A modulated diode mW laser was aimed onto the thin film and a diode detector was placed to detect the reflected laser light. In order to read the Kerr rotation, a polarizer/analyzer setup was used. A polarizer was placed between the laser and the sample, and an analyzer was placed between the sample and the detector. The rotation angle between the polarizer and analyzer was set to be nearly 90^{o}. The laser and detector were then connected to a lock-in amplifier and a signal generator. These instruments were connected to a computer running Labview, which controlled instrument setup and data acquisition during the measurement runs. The basic setup is shown in Figures 4 and 5.

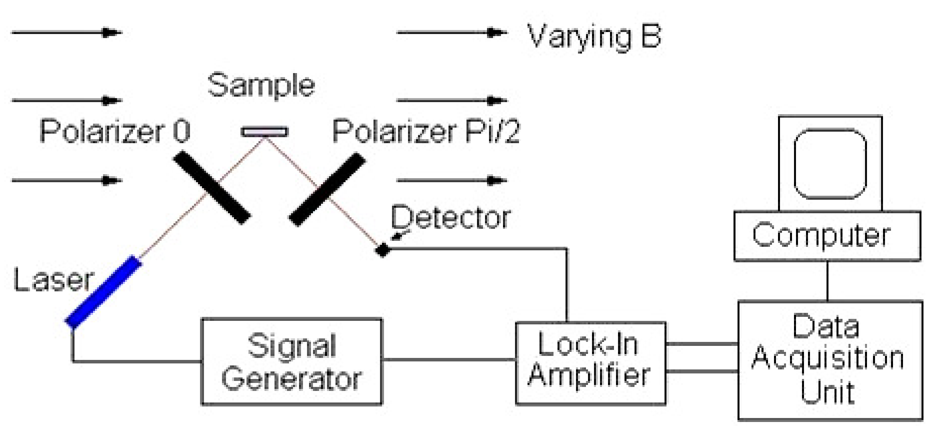


Figure 4 - MOKE Setup Concept[28] - Sample face and rotatable mount aligned parallel with applied magnetic field. Laser and diode detector counted to signal generators and lock-in amplifier, which is then routed to a computer running LabView.

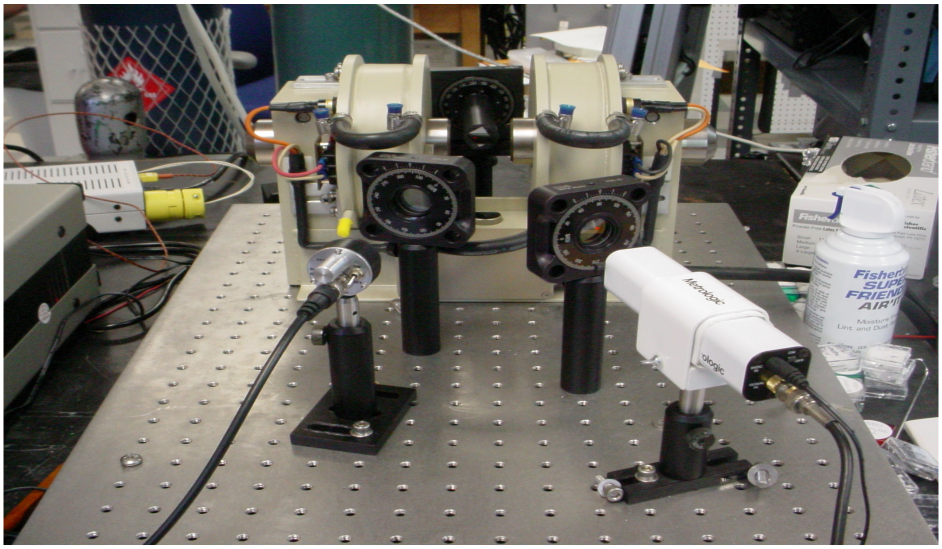


Figure 5 - MOKE Setup Actual – Rotatable mount and Helmholtz Coils in background, Laser, Diode detector, and Polarizer/Analyzer setup in foreground

The laser was modulated at a frequency of 4.958 kHz using a signal generator and this signal was used as a reference for the lock-in amplifier. In Labview, the system was set to run the Helmholtz coils at 1.25A, at a current step value of 0.05A, at a sample rate of 300ms, and at a sample per point rate of 1. The calibration equation for the Helmholtz Coils was B(Gauss) = (498.17*I(A))+1.81. As noted in the calibration equation, the applied magnetic field was recorded in terms of current, and since a diode detector was used, the magnetization of the sample was also recorded in terms of current.

III c) Experimental Procedure

The general experimental setup is relatively simple. The unpinned magnetic multilayered thin film was placed on a plate between bar magnets, in which the magnets are placed so as to align the magnetic field in one direction, with a value of approximately 40 Gauss. The plate with the thin film and magnets was then placed in a scientific oven. A thermocouple, to determine temperature, was attached to the plate, and the oven was turned on and set to the lowest setting. For the oven that is available to us, this setting corresponds to about 20 ^{o}C. The oven used had been pretested. The temperature difference between the settings was around 20-25 ^{o}C, and the highest temperature obtained was 250 ^{o}C. A summary of the temperatures obtained is given in Table 1. The sample was heated at a setting until the oven reached thermal equilibrium. The oven was turned off and the sample was then allowed to cool to room temperature while in the field provided by the bar magnets.

Setting	Temp (^{o}C)	Time from start to Temp (min)
Room	20.1	---------
1	22.4	10
2	39.4	15
3	72.4	25
4	92.3	20
5	128.7	37
6	158	40
7	181.6	57
8	209.3	86
9	228.6	72
10	245.5	118

Table 1 - Temperature data for oven used in pinning

After heating and cooling, the sample was removed from the plate and attached to the rotatable mount. The mount with the attached sample was placed between the Helmholtz Coils. To assure consistency an arrow was written indicating the direction of the applied magnetic field on pinning, on the back of the sample. The sample was placed so that the arrow was always pointed to the right. This is illustrated in Figure 6.

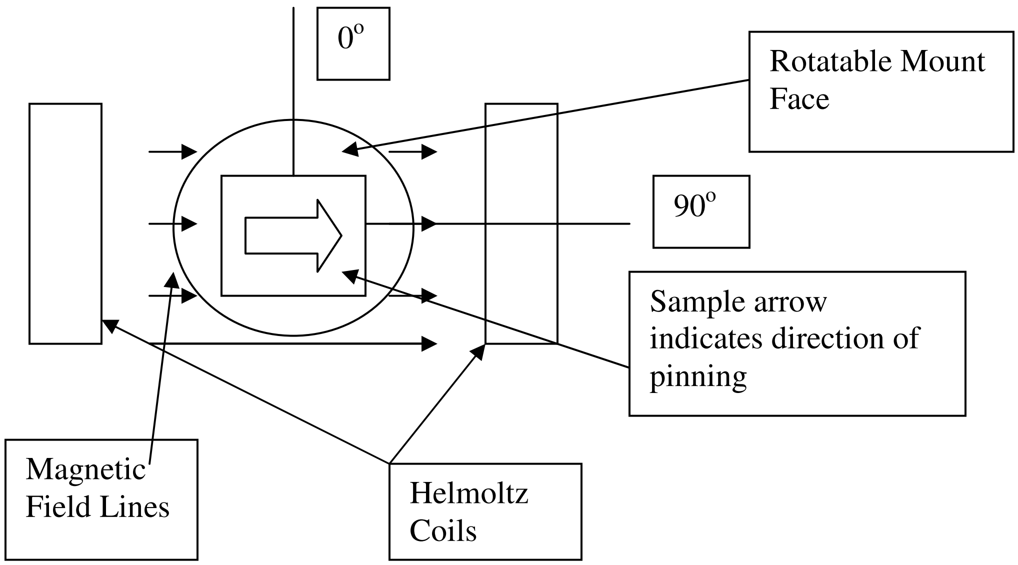


Figure 6 – Orientation of arrow on back of sample for 0° setting on rotatable mount

The whole apparatus was covered to reduce outside light, so that the diode detector would detect only the reflected laser light. A hysteresis loop of the sample was then recorded at the 0 degree mark on the face of the rotatable mount, using Labview to control the setup. The mount face was then rotated 15 degrees and another hysteresis loop of the sample was recorded. This was repeated in 15 degree increments for a complete rotation of the sample. The thin film was removed from the mount face and placed back in the same position and orientation on the plate with the magnets. To assure this, the arrow on the back of the sample was placed in the same direction on the plate, in the same orientation with respect to the magnets, for all heatings and coolings. The plate was placed back in the oven, reattached to the thermocouple, and then heated to the next higher setting, upon which the sample was allowed to cool to room temperature, and then was reanalyzed. This procedure was done until the sample had been heated to the highest setting on the oven and the MOKE procedure had been performed on it. The data from all the hysteresis loops was then analyzed for the sample's coercivity (H_c) and exchange bias (H_{eb}), by visually determining the coercivity points on both sides of the hysteresis loops and using the equations listed in Figure 2. Polar plots of these values versus the angle between the pinning direction (which should correspond to an easy axis) and the applied field were made.

IV. Results and Discussion

IV a) MOKE hysteresis loops

Figure 7 shows example MOKE curves for different angles, showing the hysteresis, the shift due to exchange bias, and the coercivity.

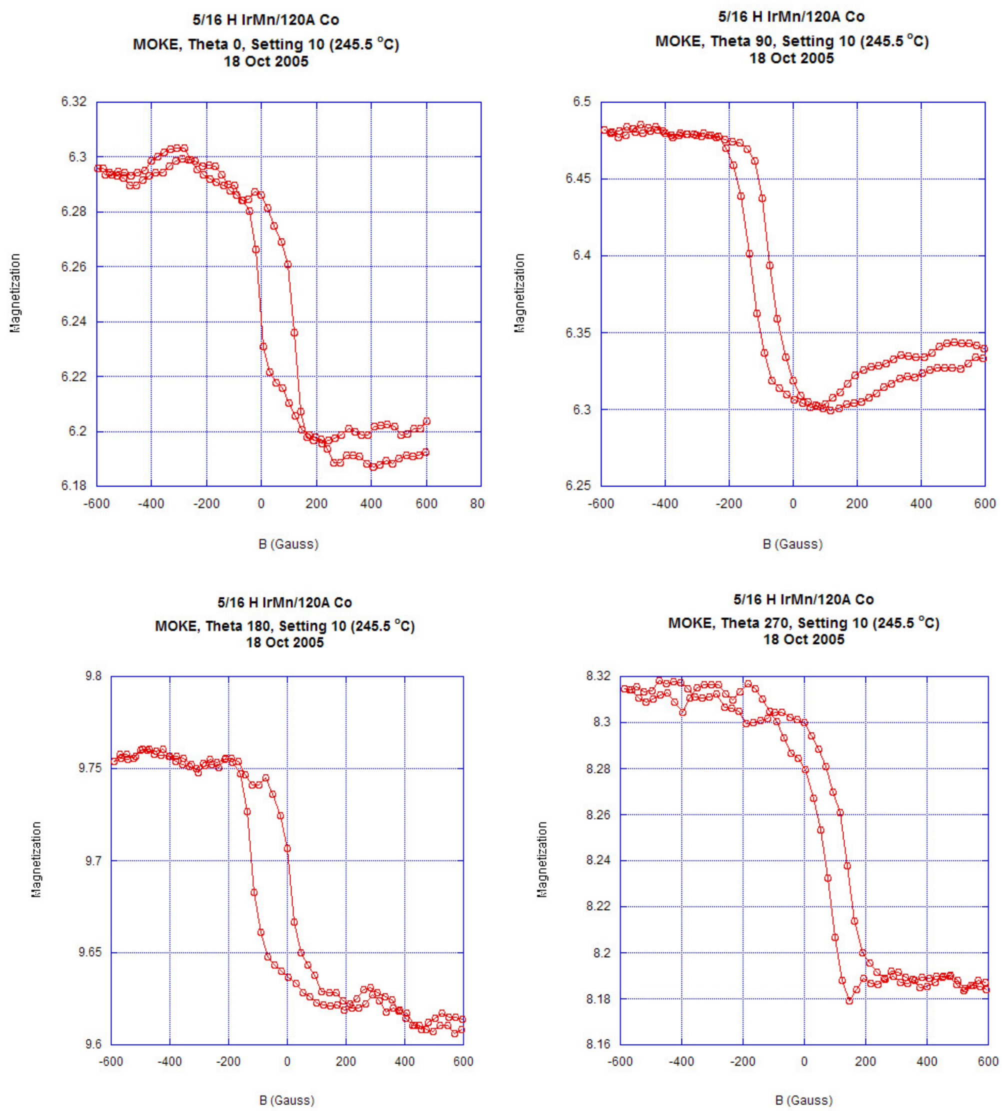


Figure 7 – Example MOKE hysteresis loops for 245.5°C heating and cooling setting. Angles theta = 0, 90, 180, and 270 are shown.

The MOKE curves were fairly repeatable in their shape and values for H_c and $H_{eb.}$ Scans to determine the repeatability of the measurements were done and their results are presented below in Tables 2 and 3. The biggest factors in determining repeatability and error were excess light that might have come from other sources than the laser, and possible sample degradation from the thermal stresses of heating and cooling the sample multiple times.

Date and scan #	H_1 (Gauss)	H_2 (Gauss)	Hc (Gauss)	Heb (Gauss)
18 Oct 2005_1	-113.33	13.33	63.33	-50.00
20 Jan 2006_1	-115.55	4.44	59.99	-55.55
20 Jan 2006_2	-115.55	4.44	59.99	-55.55
20 Jan 2006_3	-117.78	6.67	62.23	-55.55
20 Jan 2006_4	-113.89	6.67	60.28	-53.61

Table 2 – Raw data from repeatability scans for theta = 180 after heating and cooling at 245.5^{o}C

	Gauss
Standard deviation Hc (Jan)	1.075
Standard deviation Heb (Jan)	0.973
Average Hc (Jan)	60.624
Average Heb (Jan)	-55.069
% Difference for Hc (Oct/Jan)	4.273
% Difference for Heb (Oct/Jan)	10.138

Table 3 – Standard deviation for Hc and Heb, and average Hc and Heb for 20 Jan 2006 scans. Also % difference comparison for Hc and Heb between 18 Oct 2005 and 20 Jan 2006 scan averages.

IV b) Exchange Bias Field and Coercivity versus Temperature

Figure 6 shows the dependence of the coercivity and exchange bias field on the heating temperature for an angle of 0 degrees between the pinning axis and applied field.

It can be seen that changes in H_c and H_{eb} are evidenced at a relatively low temperature, around 50°C. The general shape of the dependence is similar to what has been reported, and can be phenomenologically described by a thermal activation model.[21] In our polycrystalline sample, there is a distribution of AF grain sizes, with some average energy $E_a = k_B T_a$ needed to fix the direction of the AF spins and produce pinning.[29] The exchange bias interaction should be proportional to the number of activated grains which is proportional to:

$$N \;\alpha\; e^{-(E_a / k_B T)} \qquad (2)^{29}$$

This dependence is shown in Figure 8, and describes the general tendency of the curve.

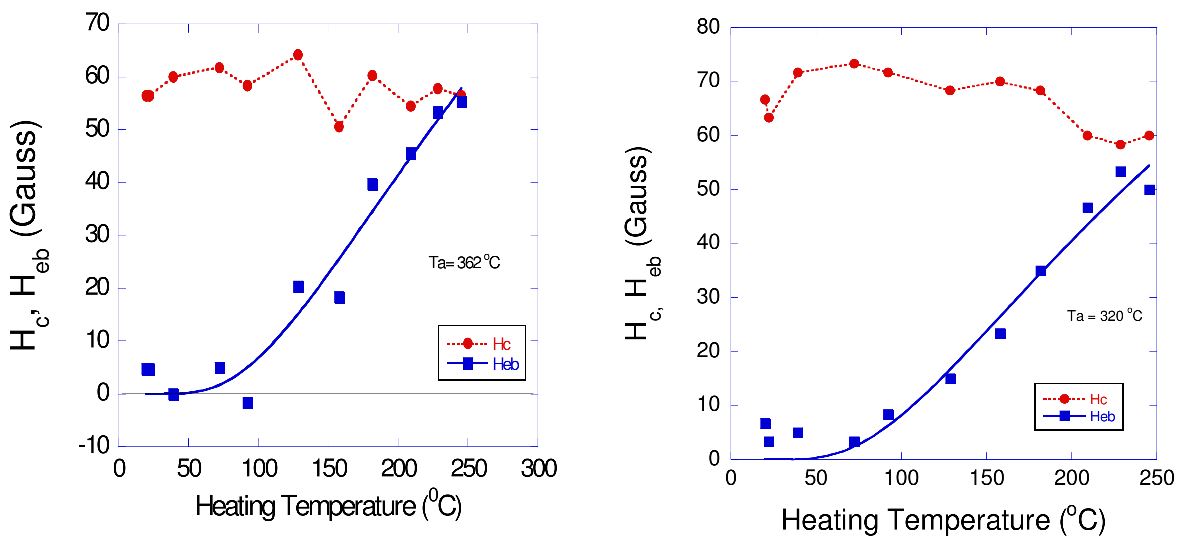
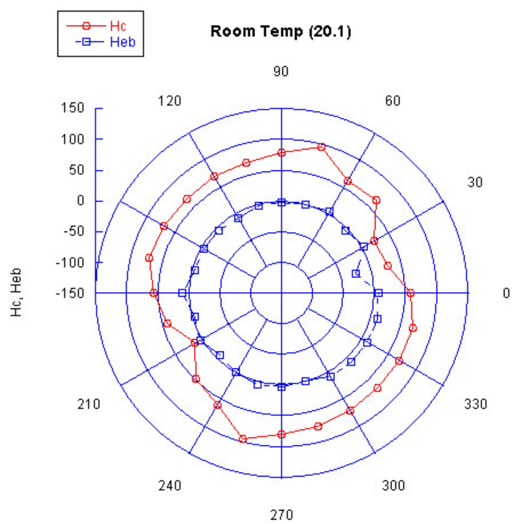


Figure 8 – Curve fit of theta = 0 (left) and theta = 315 (right) data for all temperatures studied. Fit shows that the data follows to a general trend of thermal activation, and that the determined value for exchange bias saturation is 362°C for theta = 0 and 320°C for theta = 315.

IV c) Angle Dependent Data and Anisotropy

The following plots show the evolution of H_c and H_{eb} as the heating temperature is increased. The data is shown as a function of angle between the pinning axis and applied field, both as a polar plot and a linear plot side-by-side. For the sample before heating, we expect a completely symmetric shape, indicating no preferred angle or axis (no anisotropy). This is approximately what is seen. The exchange bias field is zero



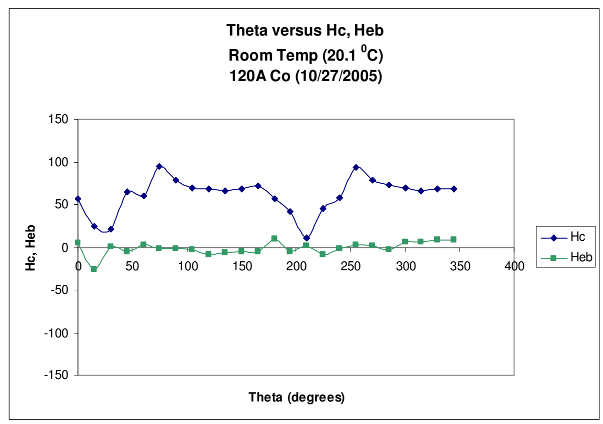


Figure 9. Angle dependent plots before sample was heated (room temperature).

(within error) at all angles. There is some anisotropy in H_c, as can be seen by dips at about 30 and 210 degrees, and can indicate some residual exchange bias interaction.

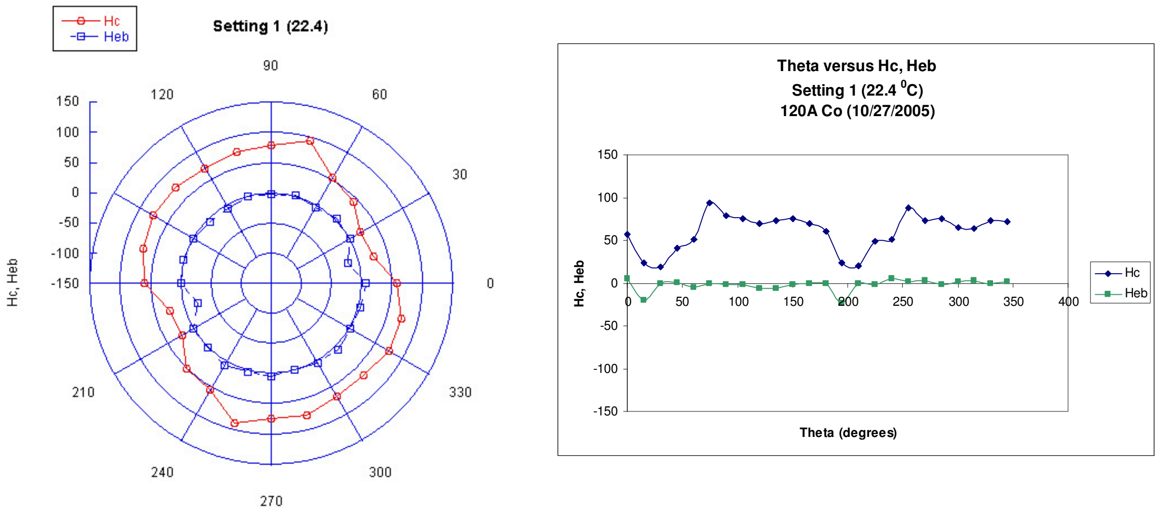


Figure 10. Angle dependent plots when sample heated and cooled from 22.4^{o}C.

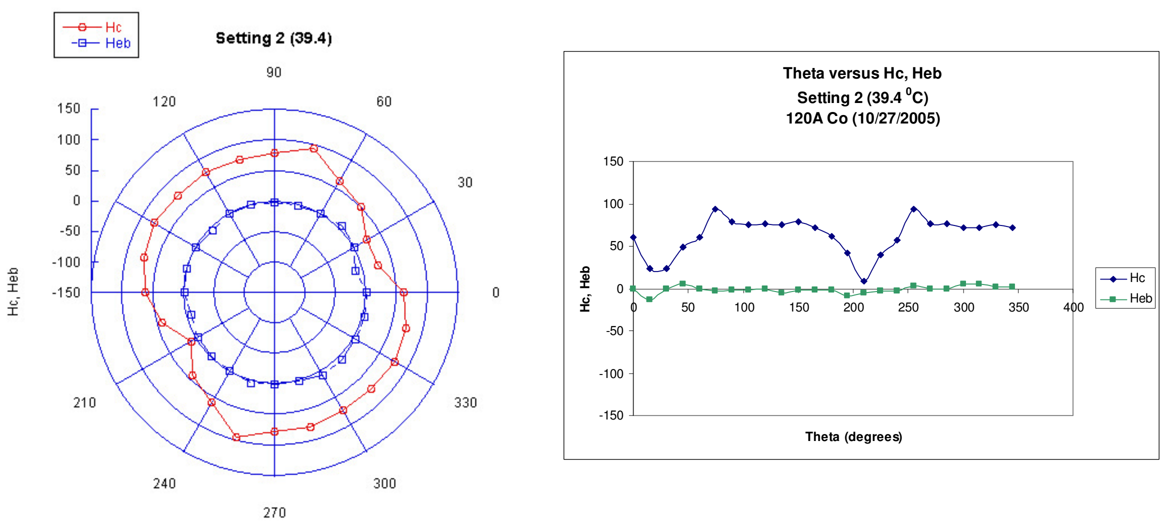


Figure 11. Angle dependent plots when sample heated and cooled from 39.4^{o}C.

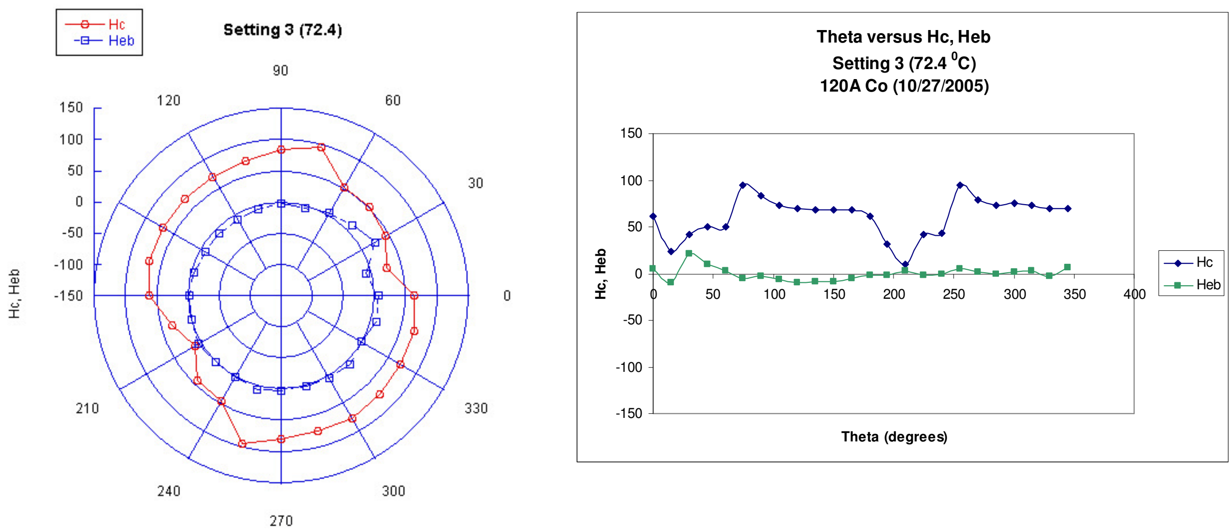


Figure 12. Angle dependent plots when sample heated and cooled from 72.4^{o}C.

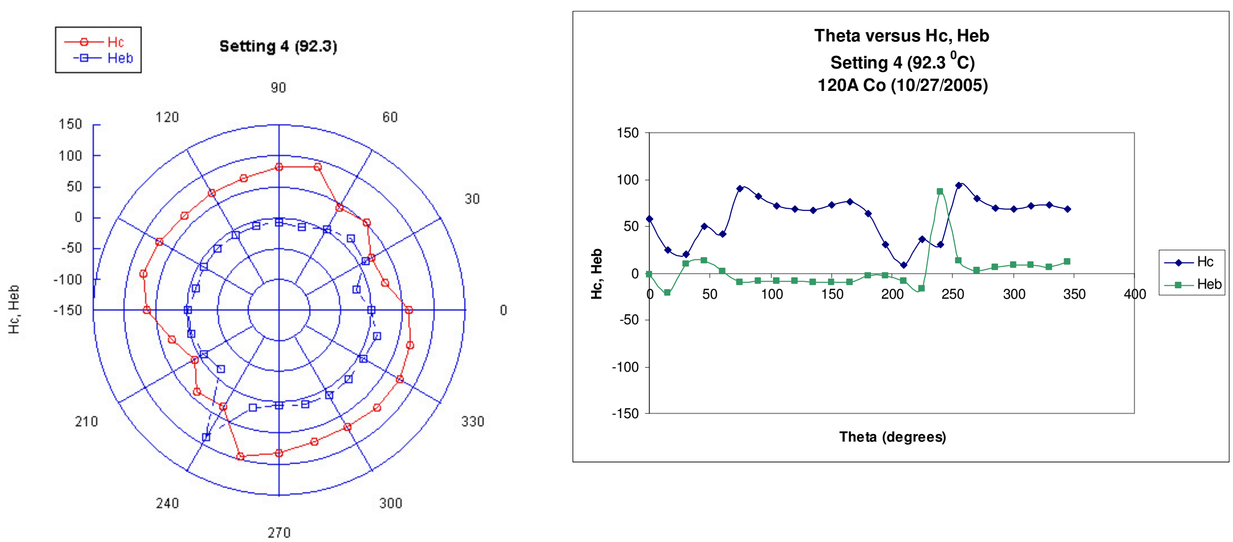


Figure 13. Angle dependent plots when sample heated and cooled from 92.3^{o}C.

For heating up to 92.3^{o}C, there are some small changes in coercivity, along with some exchange biasing appearing. The exchange bias direction appears around 240^o and 30^o.

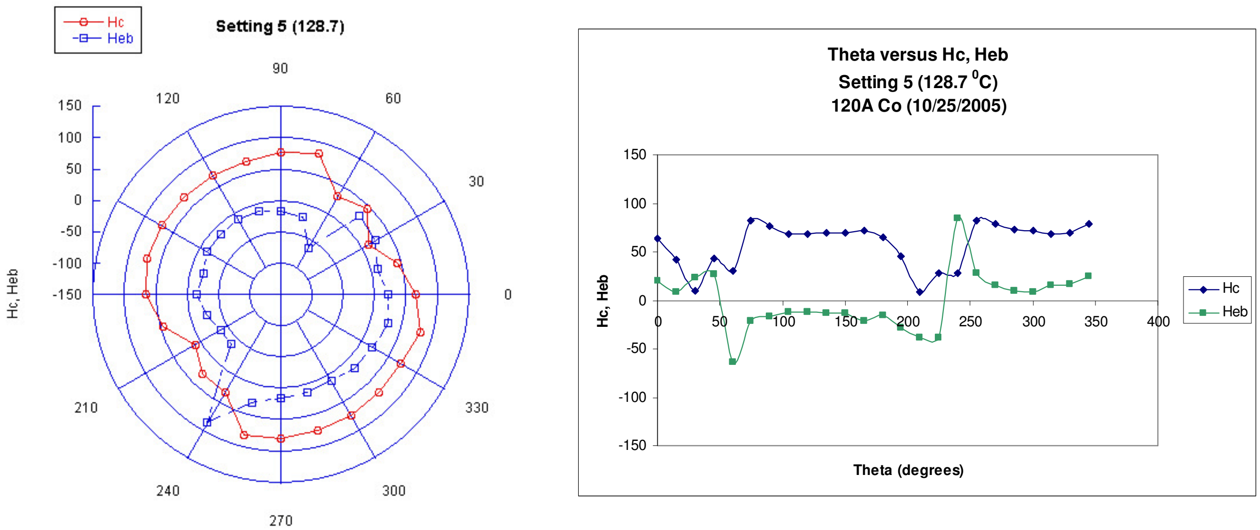


Figure 14. Angle dependent plots when sample heated and cooled from 128.7^{o}C.

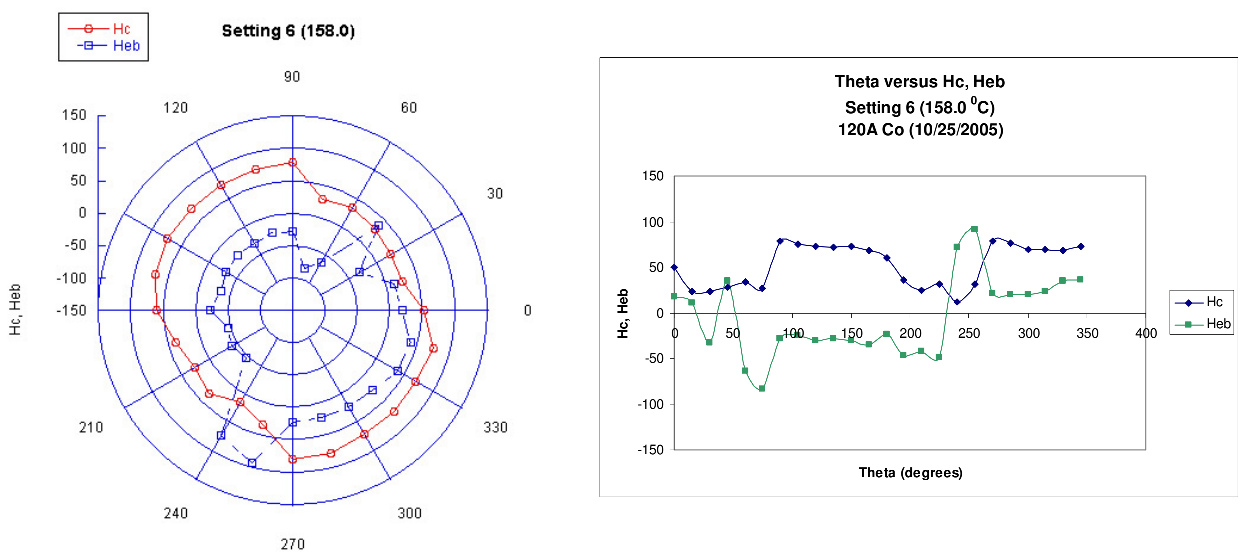


Figure 15. Angle dependent plots when sample heated and cooled from 158^{o}C.

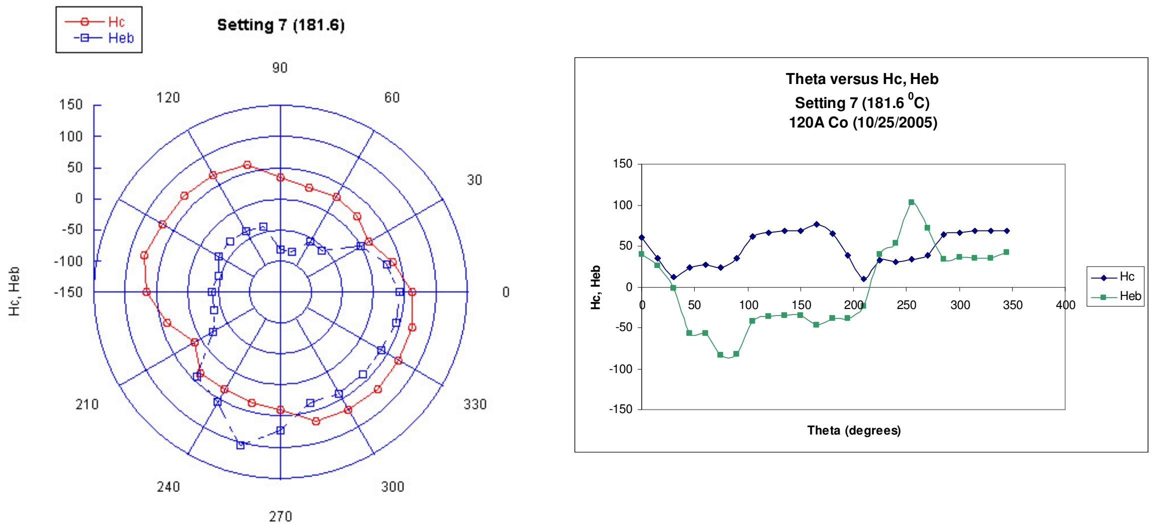


Figure 16. Angle dependent plots when sample heated and cooled from 181.6^{o}C.

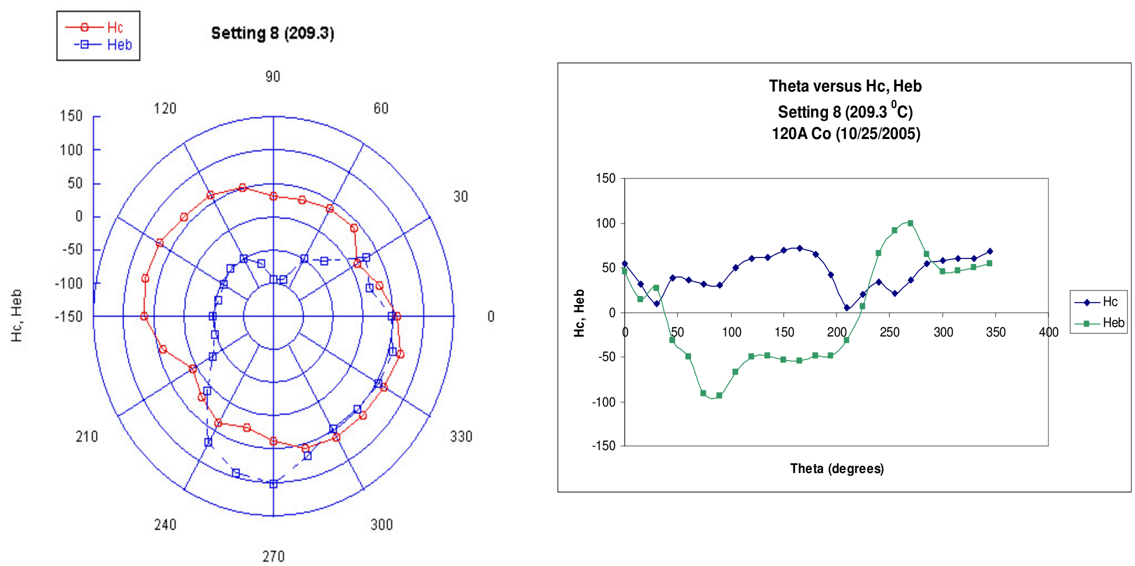


Figure 17. Angle dependent plots when sample heated and cooled from 209.3^{o}C.

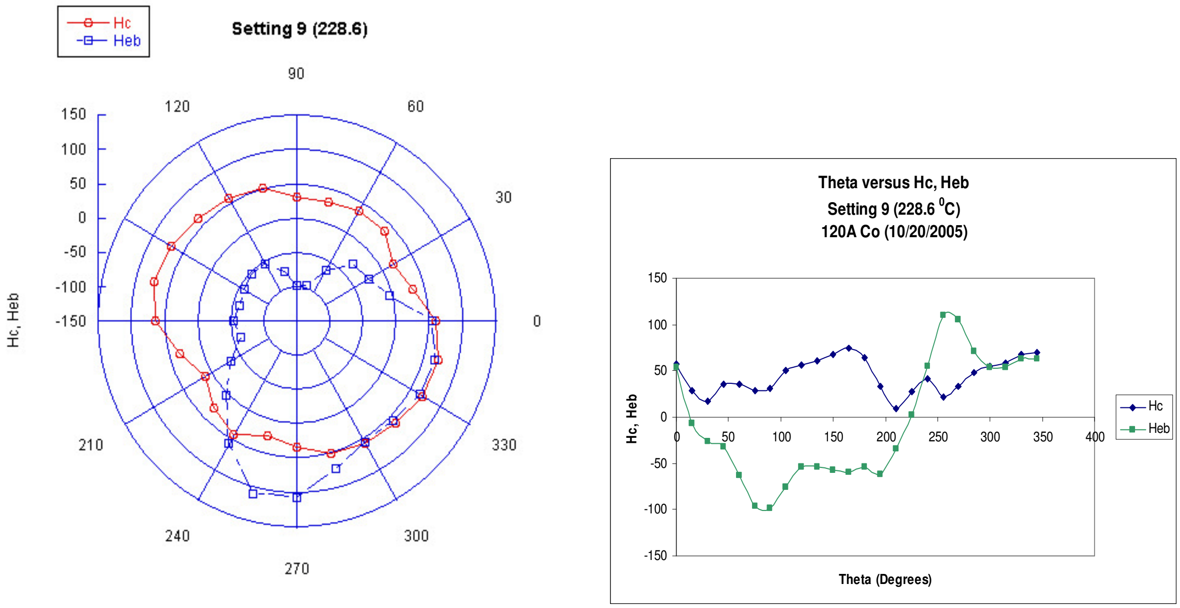


Figure 18. Angle dependent plots when sample heated and cooled from 228.6°C.

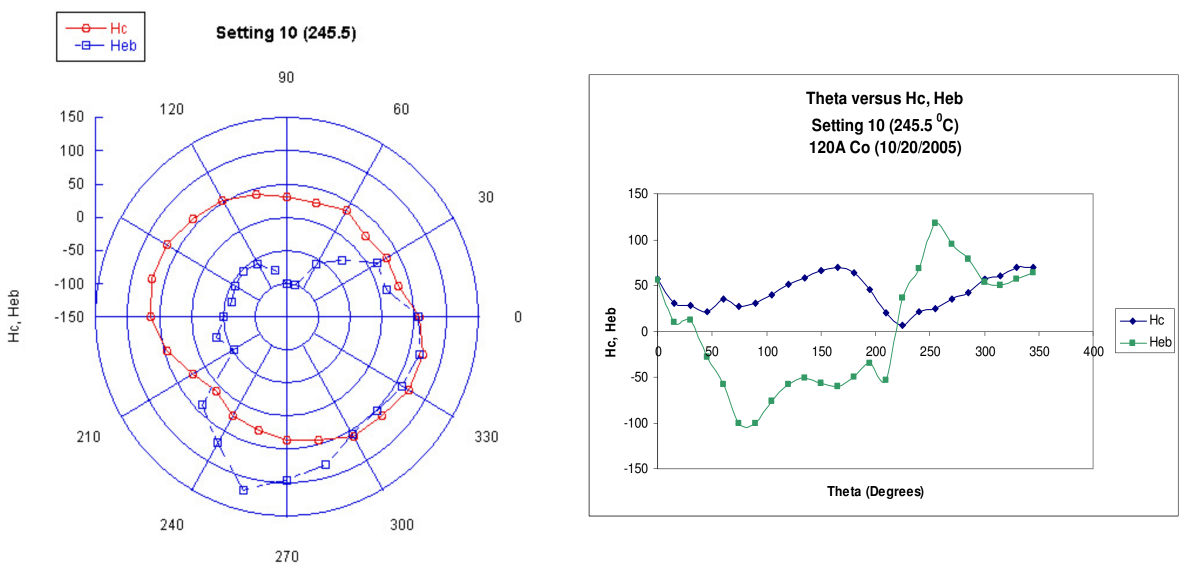


Figure 19. Angle dependent plots when sample heated and cooled from 245.5°C.

According to the low temperature scans, angles 30 and 210 are hard axes, while angles 75 and 255 are easy axes. This was determined from the coercivity. When the coercivity of a material is rather large, then its electron's spins are oriented along an easy axis of the material.[6] Conversely, when its coercivity is rather small, its electrons' spins are along a hard axis of the material.[6]

The temperature effects of the study are also quite interesting on preliminary review. The coercivity remains relatively the same until the 72.4 ^{o}C scan. Here the peaks as presented on the linear plots started to soften and form wider wells. As the temperature increased, the amplitude of the coercivity began to decrease. It is assumed at the moment that the sample degraded at the higher temperatures, in which the interfaces of the sample began to blur together affecting the spin properties of the sample thus reducing the coercivity.

The exchange bias was relatively unchanged until the 92.3 ^{o}C scan, when an anisotropic spike appeared at 240^{o} on the polar plot. At the next temperature setting, 128.7^{o}C, the changing exchange bias resulted in another spike at 45^{o} and a broadening of the exchange bias on one side of the film. These results continued up to 158 ^{o}C, but by the scan at 181.6 ^{o}C the anisotropy of the material was essentially gone. Simple uniaxial anisotropy, which would be expected, did not appear. There is a general appearance of exchange biasing (shift in the hysteresis loops) but it is evidenced over a wide range of angles. At 181.6 ^{o}C, the exchange bias was large and expansive on one side of the film, but not in any one direction. This persisted up to the maximum temperature measured, 245.5 ^{o}C. One thing of note is that the amplitude of the exchange bias did not change during these higher temperature intervals. It is assumed at the moment that the sample had a low blocking temperature, based on the 110 ^{o}C value that Anderson and et al. determined for their IrMn 50Å spin value system, which caused the multiple gradual changes in peaks.[4]

IV d) Modeling of Angle Dependence

A relatively new model has been published by Radu, et al. which was designed for their IrMn/CoFe system.[30] In their article, they modified the Meiklejohn and Bean model of AF/F interactions to account for spin disorder (SD) at the AF/F interface.[30] They did this because it is their assumption that the SD layer plays a major role in reducing the exchange bias and conveying the coercivity from the AF to the F layer.[30] Their model gives as the energy of the system:

$$\mathrm{E} = \begin{array}{l} -\mu_o H M_F t_F \cos(\theta-\beta) + K_F t_F \sin^2(\beta) - \mu_o H M_{SD} t_{SD} \cos(\theta-\beta) \\ + K_{SD}^{eff} \sin^2(\beta-\gamma) + K_{AF} t_{AF} \sin^2(\alpha) - J_{EB}^{eff} \cos(\beta-\alpha) \end{array} \qquad (3)^{30}$$

Where J_{EB}^{eff} is the reduced interfacial exchange energy, γ, for $\gamma \geq 0$, is the average angle of the effective SD anisotropy, α is the average angle of the AF uniaxial anisotropy, M_{AF} is the magnetization of the SD interface, t_{SD} is the SD interface thickness, K_{SD}^{eff} is the effective average anisotropy for spin, and θ and β are the observables from their vector MOKE measurements.[30]

To date, not much progress has been made in modeling the below results using this model, because of a current lack of information pertaining to some unknown constants and variables in the above equation that are system specific. The modeling results of their vector MOKE measurements were uncannily accurate and despite the fact that they were working with a different magnetic thin film system their theta versus H_{eb}/ H_c plots were similar to plots obtained here,[30] so further progress using this model is hoped to be made in the immediate future.

V. Conclusion

A study of the onset of exchange bias interaction in an AF/F multilayer as a function of sample heating temperature has been undertaken. Effects on both the hysteresis loop shift (H_{eb}) and coercivity (H_c) were seen, even at relatively low temperatures. The changes induced followed a general dependence seen by other researchers and can be qualitatively described by thermal activation. For this particular sample, however, clear uniaxial anisotropy was not observed. This may be because of the structure of the sample, because the pinning field was low (~40 G) or because we could only pin to 250^{o}C.

To improve this study further, data would need to be taken above 250^{o}C. This would provide us with data above the assumed Néel temperature of the AF, and would also hopefully show the saturation point of the exchange bias of the system. Also the system dependent constants and values for the model proposed by Radu, et al. would need to be determined or obtained through a literature search in order to utilize their model. Finally, analysis of different types of magnetic thin film samples would broaden the study and provide hopefully better insight into the exchange bias properties of these thin film systems.

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