Magnetic Hysteresis Curves of Thin Films under Isotropic Stress

## THESIS

Presented to the Graduate Council of

Southwest Texas State University

in Partial Fulfillment of

the Requirements

For the Degree

Master of Science

By

Patrick J. Holland

San Marcos, Texas

May, 2001

#### ACKNOWLEDGMENTS

First I thank my parents for their love, kindness, and support of my education over the years. Many thanks to Dr. Ir. Wilhelmus Geerts whose scholarly attention and dedication have taught me much. Many thanks to my thesis committee members Dr Donald Olson and Dr Heather Galloway for their time, effort and advice. I appreciate the instruction of Drs Victor Michalk, Carlos Gutierrez, William Jackson, and chairman James Crawford of the SWT Physics Department. Dan Millikin provided well needed electronics advice and equipment for this research. And finally I appreciate the help I have received from the following of my peers over the years: Mike Matheaus, Charlie Watts, Jett Hendrix, Anival Ayala, Kevin Wiederhold and Paul Person.

Thank you.

# **TABLE OF CONTENTS**

# Page

ACKNOWLEDGMENTSv
LIST OF FIGURES ix
ABSTRACT xvi
CHAPTER 1. INTRODUCTION1
CHAPTER 2. STRESS
CHAPTER 3. FERROMAGNETIC AND MAGNETOELASTIC
PROPERTIES14
3.1 FERROMAGNETISM14
3.2 MAGNETIC ANISOTROPY18
3.3 MAGNETOSTRICTION22
3.4 STRESS AND MAGNETIC PROPERTIES24
3.5 THIN FILMS
3.6 APPLICATIONS
CHAPTER 4. MAGNETO-OPTICAL KERR EFFECT
4.1 POLARIZED LIGHT
4.2 ELLIPSOMETRY
4.3 MODULATED ELLIPSOMETRY
4.4 MAGNETO-OPTICAL KERR TRACER40

4.5 OTHER ELLIPSOMETERS46
4.6 QUANTUM MECHANICS46
CHAPTER 5. EQUIPMENT SETUP47
5.1 MONOCHROMATIC AND SPECTROSCOPIC ELLIPSOMETER
47
5.2 POLARIZER AND ANALYZER48
5.3 PHOTOELASTIC MODULATOR48
5.4 QUARTER WAVE PLATE, LENSES, AND HELIUM NEON
LASERS49
5.5 PHOTO-DIODE, DETECTION ELECTRONICS,
ELECTROMAGNET, AND GAUSSMETER50
5.6 XENON ARC LAMP51
5.7 MONOCHROMATOR51
5.8 PHOTOMULTIPLIER TUBE
CHAPTER 6. SAMPLE PREPARATION
CHAPTER 7. RESULTS
7.1 ALUMINUM OXIDE IRON MATRIX57
7.2 THICK NICKEL IRON 35% FILMS (500 NM)58
7.3 THIN FILMS (100 NM)62
7.4 STRESS DEPENDENCE MEASURED THROUGH GLASS
SUBSTRATE65
7.5 SUMMARY66
CHAPTER 8. CONCLUSION

8.1 SUMMARY	68
8.2 RECOMMENDATIONS FOR FUTURE STUDY	69
APPENDIX	70
1. SPUTTERING PARAMETERS	71
2. SPECTROSCOPY SYSTEM	74
3. PHOTOMULTIPLIER ELECTRONICS	83
4. EQUIPMENT SPECTRAL RESPONSE	85
BIBLIOGRAPHY	98

# **LIST OF FIGURES**

Page

FIGURE 2.1. EXTERNALLY APPLIED STRESS
FIGURE 2.2. RESIDUAL STRESS STRESSES AND THE EFFECTS ON THE
FILM-SUBSTRATE INTERFACE8
FIGURE 2.3. PICTURE OF PRESSURE CELL AND SCHEMATIC9
FIGURE 2.4.GASKET STRATEGY9
FIGURE 2.5. EXPERIMENTAL SETUP TO DETERMINE THE RADIUS OF
CURVATURE OF THE SAMPLE10
FIGURE 2.6.NICKEL IRON ON GLASS12
FIGURE 2.7. SILICON SUBSTRATE 0.7MM THICK12
FIGURE 2.8. COPPER FOIL SUBSTRATE13
TABLE 2.1. SUBSTRATE LIMITS    13
FIGURE 3.1.HYSTERESIS CURVE14
FIGURE 3.2.MAGNETIC DOMAINS15
FIGURE 3.3. 3D AND 4S ELECTRON ORBITALS FOR FERROMAGNETIC
METALS AND COPPER17
FIGURE 3 4. ANISOTROPY OF THE MAGNETIZATION CURVES OF IRON
ALONG THE 3 MAJOR CRYSTAL AXES19

FIGURE 3.5. ANISOTROPY OF THE MAGNETIZATION CURVES OF NICKEL ALONG THE 3 MAJOR CRYSTAL AXIS .....20 FIGURE 3.6. COMPOSITIONAL DEPENDENCE OF K1 ANISOTROPY CONSTANT FOR ORDERED AND DISORDERED NI-FE FIGURE 3.7. PHASE DIAGRAM FOR NI-FE ALLOY ......21 FIGURE 3.8. EFFECTS OF MAGNETOSTRICTION ON ATOMIC ORBITALS TABLE 3.1. MAGNETOSTRICTION OF POLYCRYSTALLINE FIGURE 3.9. EFFECT OF TENSION ON THE MAGNETIZATION OF A **MATERIAL WITH POSITIVE MAGNETOSTRICTION 25** FIGURE 3.10. EFFECTS OF TENSILE STRESS ON MAGNETOSTRICTION FIGURE 3.11. EFFECT OF TENSILE STRESS ON THE MAGNETIZATION FIGURE 3.12. MAGNETIZATION OF A MATERIAL WITH POSITIVE MAGNETOSTRICTION UNDER TENSILE STRESS....27 FIGURE 3.13. MAGNETIZATION OF A MATERIAL WITH POSITIVE MAGNETOSTRICTION UNDER COMPRESSIVE STRESS FIGURE 3.14 INDUCTION MEASUREMENTS CAN BE MADE WITH TWO 

FIGURE 3.15 MICROSTRUCTURE OF A MAGNETIC SENSOR30
FIGURE 4.1. THE DEFINITION OF PHASE DIFFERENCE AND AMPLITUDE
RATIO FOR LINEARLY POLARIZED LIGHT, CIRCULARLY
POLARIZED LIGHT, AND ELLIPTICALLY POLARIZED
LIGHT
FIGURE 4.2. SHOWING THE EFFECT OF THE CHANGE OF SOP AT
<b>REFLECTION (A) WITH A NON-MAGNETIC MATERIAL</b>
FIGURE 4.3. DIAGRAM OF A NULL ELLIPSOMETER35
FIGURE 4.4. THE PHASE SHIFT BETWEEN TWO ORTHOGONAL
COMPONENTS OF ELLIPTICALLY POLARIZED LIGHT
DEPENDS ON COORDINATE SYSTEM
FIGURE 4.5. MODUALTED ELLIPSOMETRY
FIGURE 4.6. MAGNETO-OPTIC KERR ROTATION AND KERR
ELLIPTICITY40
FIGURE 4.7. RETARDATION (A), SOP OF REFLECTED BEAM, S-
COMPONENT OF THE REFLECTED LIGHT, AND
INTENSITY WITH NO KERR EFFECT (B), WITH KERR
ROTATION (C), WITH KERR ELLIPTICITY (D)45
FIGURE 5.1. MONOCHROMATIC KERR ELLIPSOMETER47
FIGURE 5.2. BIREFRINGENCE OF A POLARIZING FILTER48
FIGURE 5.3. MODULATION BY THE PEM

FIGURE 6.1. INTERIOR COMPONENTS OF THE TORAYDC MAGNETRON

FIGURE 7.1 1 KERR HYSTERESIS CURVES AT DIFFERENT PRESSURES FOR A MATRIX OF FeAl<sub>2</sub>O<sub>3</sub> on SiAl<sub>2</sub>O<sub>3</sub>......57 FIGURE 7.2. HYSTERESIS CURVES OF 500NM OF NIFE35% MEASURED FIGURE 7.3. HYSTERESIS CURVES OF 500NM OF NIFE35% MEASURED WITH INTENSITY REGULATED HENE LASER .......59 FIGURE 7.4. KERR HYSTERESIS CURVES OF A NIFE35% SAMPLE THAT HAS BEEN REMOVED FROM THE PRESSURE CELL, CLEANED OF GREASE, REMOUNTED IN THE PRESSURE FIGURE 7.5. COERCIVITY VERSUS PRESSURE FOR NIFE35% .....60 FIGURE 7.6. KERR HYSTERESIS CURVES OF A NIFE35% SAMPLE THAT HAS BEEN REMOVED FROM THE PRESSURE CELL, CLEANED OF GREASE, REMOUNTED IN THE PRESSURE CELL AND MEASURED AGAIN ......60 FIGURE 7.7. REPEAT MEASUREMENT OF THE SAME SAMPLE AS FIGURE 7.8. KERR HYSTERESIS CURVES OF 100NM OF NIFE35% MEASURED WITH A STANDARD HENE LASER ......62

# FIGURE 7.9. KERR HYSTERESIS CURVES OF 100NM OF NIFE35% MEASURED WITH A INTENSITY REGULATED HENE LASER......63 FIGURE 7.10. RE-MEASUREMENT KERR HYSTERESIS CURVES OF 100NM OF NIFE35% MEASURED WITH A INTENSITY FIGURE 7.11. COERCIVITY VERSUS PRESSURE FOR 100NM FILM OF FIGURE 7.12. KERR HYSTERESIS CURVES WITH THE SUBSTRATE **INSERTED BACKWARDS IN THE PRESSURE CELL.65** FIGURE 7.13. COERCIVITY VERSUS PRESSURE WITH THE SUBSTRATE BACKWARDS......66 FIGURE 7.14. COMPARISON OF THE COERCIVITY OF THE 3 TYPES OF SAMPLE MEASURED WITH INCREASING PRESSURE. TABLE A1.1 NICKEL-IRON SAMPLE PREPARATION ......72 FIGURE A2.1. EQUIPMENT SETUP FOR MEASURING ABSORPTION SPECTRA......74 TABLE A2.1. LENS FOCAL LENGTH AND DIAMETERS......74 FIGURE A2.2. EMISSION SPECTRUM OF XENON ARC LAMP ......75 FIGURE A2.3. ABSORPTION SPECTRUM OF STANDARD LAB SAFETY

FIGURE A2.4. TRANSMITTANCE OF STANDARD LAB SAFETY GLASSES

FIGURE A2.5. ABSORPTION SPECTRUM OF UV-PROTECTION GLASSES

FIGURE A2.6. TRANSMITTANCE OF UV-PROTECTION GLASSES 77

FIGURE A2.7. ABSORPTION SPECTRUM OF POLAROID SUNGLASSES

......77

FIGURE A2.8. TRANSMITTANCE OF POLAROID SUNGLASSES ...77

FIGURE A2.9. ABSORPTION SPECTRUM OF AR LASER UV-PROTECTION

GOGGLES......78

FIGURE A2.10. TRANSMITTANCE OF AR LASER UV-PROTECTION

FIGURE A2.11. ABSORPTION SPECTRUM OF UV-PROTECTION

FIGURE A2.12. TRANSMITTANCE OF UV-PROTECTION GOGGLES

FIGURE A2.13. EMISSION SPECTRUM OF XENON ARC LAMP.....79

FIGURE A2.14. ABSORPTION SPECTRUM OF 1 SHEET OF BILAYERED

FIGURE A2.15. TRANSMITTANCE OF 1 SHEET OF BILAYERED FILTER

FILM ......80

FIGURE A2.16. ABSORPTION SPECTRUM OF 2 SHEET OF BILAYERED

FILTER FILM......80

FIGURE A2.17. TRANSMITTANCE OF 2 SHEET OF BILAYERED FILTER
FILM80
FIGURE A2.18. ABSORPTION SPECTRUM OF 4 SHEET OF BILAYERED
FILTER FILM81
FIGURE A2.19. TRANSMITTANCE OF 4 SHEET OF BILAYERED FILTER
FILM81
FIGURE A2.20. ABSORPTION SPECTRA OF 1 SHEET OF MONOLAYERED
FILTER FILM81
FIGURE A2.21. TRANSMITTANCE OF 1 SHEET OF MONOLAYERED
FILTER FILM
FIGURE A3.1. PHOTOMULTIPLIER ELECTRONICS

#### ABSTRACT

#### Magnetic Hysteresis Curves of Thin Films under Isotropic Stress by PATRICK J. HOLLAND, M.S. Southwest Texas State University May 2001

#### **SUPERVISING PROFESSOR: WILHELMUS J. GEERTS**

Magnetic properties of materials have been of increasing importance in recent years due to their many uses in high tech devices. New materials are being sought for magneto-optical storage, magnetic random access memory, and magnetic sensors. Stress, both intrinsic and extrinsic, can affect magnetic properties, such as altering the magnetic anisotropy and coercive force. To study the effects of external stress, a pressure cell was constructed to apply isotropic biaxial stress to thin magnetic films on glass and metal substrates. Thin films of NiFe 35% were deposited on glass substrates by DC magnetron sputtering. For 500 nm thick films the coercivity decreased with increasing pressure. The relation between coercivity and pressure appeared to be linear which makes these films very interesting for use in magnetic sensor devices. For 100 nm thick films there was no observed change in coercivity with applied pressure. This difference for thin films suggest a different magnetic reversal process at work. This work has been previously presented at the following seminars:

Texas Section APS fall-meeting, Houston, Rice University, October 2000 Patrick J. Holland, Archana Dubey, Wilhelmus J. Geerts,

Magnetic Hysteresis Measurements of Thin Films under Isotropic Stress.

Department of Physics Seminar, Southwest Texas State University, July, 2000, December 2000, Patrick J. Holland Effects of Isotropic Stress on Thin Magnetic Films July, 1999, Patrick J. Holland A Spectroscopy System for Ellipsometry

# **CHAPTER 1**

#### **INTRODUCTION**

Investigation into the properties of magnetic materials has been increasing in recent years due to the demand for their use in data storage devices, sensors, actuators and transformers. Methods of changing magnetic properties by stress provide a convenient way of altering material properties. Stress can be internal such as the lattice strain caused during a deposition process, or external such as bending or compression of the substrate (see chapter 2). The purpose of this investigation is to apply an external stress to thin magnetic films and measure how magnetic properties of the film change as measured by the magneto-optical Kerr effect.

Effects of stress on anisotropy are important in magneto-optic storage media. This application calls for materials with large Kerr rotation at short wavelengths, coercivity that is large at room temperature and low at 200°C, and a strong uniaxial anisotropy with easy axis perpendicular to the plane of the film.<sup>1</sup>

Other forms of magnetic storage include magnetic random access memories. Several different approaches are possible such as giant magnetoresistance materials, anisotropic magnetoresitance materials<sup>2</sup>, and stress operated magnetorestrictive devices. Novosad's<sup>3</sup>

device incorporates magnetic particles in a piezoelectric array. Two pairs of contacts are used to rotate the stress at one point on the grid and elicit a reversal of magnetization.

Another use for application of stress and magnetic materials is design and construction of stress sensors. It has been found that in piezomagnetic materials, materials that change length in a magnetic field, the essential requirement for use as a sensor is a well defined domain structure dominated by uniaxial anisotropy.<sup>4</sup> For bulk materials Garshelis<sup>5</sup> found a decrease in coercivity with tension and an increase and subsessequent decrease of coercivity with applied compression. Sablik<sup>6</sup> describes an asymmetry with respect to stress variation due to a demagnetization term to explain the difference between tensile stress and compressive stress. He suggests the demagnetization is caused by how different orientations of grain surfaces react differently to compression and tension.

The effects of stress during deposition has been found to affect anisotropy and magnetostriction.<sup>7, 8,9,10</sup> Callegaro and Puppin<sup>11,12</sup> suggest a method for investigating the total stress state of a material by applying external stress to a magnetic film which acts as a perturbation on the internal stress state. They examined nickel films electroplated on polished copper disks. A pressurized membrane cell was used to apply uniaxial stress to the sample. For polar Kerr hysteresis curves the coercive force was reduced by 20% at a strain of 10<sup>-3</sup>.

A similar system is chosen for this study. NiFe35% films of 2 different thicknesses were sputtered onto glass substrates and by use of high pressure gas against the bottom of the substrate the film is placed under in-plane isotropic stress. Magnetic

2

hysteresis curves were measured by the magneto-optical Kerr effect. Different substrates were examined for effectiveness in various stress regimes.

#### **CHAPTER 2**

#### **STRESS**

The effects of stress on magnetic properties of a material can be quite substantial and provides the motivation for this investigation. Stress is defined as the magnitude of force per unit area required to cause an elastic deformation.

$$\varepsilon = \frac{F}{A} \left[ \frac{N}{m^2} \right]$$
 [2.1]

The strain resulting from the applied stress is the change in a quantity, such as length, surface area, or volume, divided by that quantity as given in Eqns. 2.2 to 2.4. Feynman<sup>13</sup> refers to strain as the fractional stretch. It is a dimensionless quantity.  $\sigma_L$  is the strain resulting from tensile or compressive stress,  $\sigma_S$  from deformation of a surface, and  $\sigma_V$  from a volume deformation.

$$\sigma_{V} = \frac{\Delta V}{V} \qquad [2.2]$$

$$\sigma_{S} = \frac{\Delta S}{S} \qquad [2.3]$$

$$\sigma_{L} = \frac{\Delta L}{L} \qquad [2.4]$$

Tensile stress enlarges an object in the direction of the applied stress. Compressive stress causes the dimensions of the object along the stress axis to decrease. If the strain is

elastic then the object will return to its un-stressed state when the stress is removed. Stress can be applied externally such as the bending of a rod or the inflation of a balloon (see Fig. 2.1). Stress in a material can also originate internally from the structure and composition of the material. If a material is in the elastic regime then the elongations will be proportional to the stress and will disappear when the stress is removed. Hooke's law,  $F = k\Delta L$ , is often used to describe the linear effects of elastic changes. An alternative form shows the linear relationship between stress and strain in the elastic regime.

$$\varepsilon = \frac{F}{A} = Y(\frac{\Delta L}{L_0}) = Y\sigma_1 \qquad [2.5]$$

Y is known as Young's modulus and is a property of the material. Thus stress is equal to Young's modulus times the strain. In the directions perpendicular to L there will be a contraction proportional to the strain.

$$\frac{\Delta W}{W} = \frac{\Delta H}{H} = -\sigma \frac{\Delta L}{L}$$
[2.6]

 $\sigma$  is called Poisson's ratio and along with *Y* completely specifies the elastic properties of a homogenous isotropic material. For crystalline materials a tensor may be used in place of the two constants.<sup>12</sup>



Fig. 2.1 Externally applied stress: (a) bent beam method, (b) inflated balloon method.

At stress levels above the limit of elastic response irreversible plastic effects occur. Examples include mechanical forming operations such as rolling, extrusion, drawing, as well as failure phenomena like creep, fatigue, and fracture.<sup>14</sup>

Figure 2.1 shows two known methods that are widely used to apply a stress to a material. The average stress in the bent rod of Fig. 2.1a is zero, with tensile stress at the top and compressive stress at the bottom of the rod. The dashed line through the middle of the rod is the line of zero stress. By bending the beam a tensile stress can be applied to a thin film on top of the beam and a compressive stress can be applied to a thin film at the bottom of the beam. Another way to apply a stress externally is to stretch the material or substrate. This technique is difficult as large forces or very thin substrates are required. Shearing stress can be created by applying equal and opposite forces to the opposite sides then the material will not be in equilibrium and a net torque will act on the material.

Internal stress in thin films can be caused by several different mechanisms. Lattice mismatch between the thin film and substrate can cause stress. If the film and substrate have different coefficients of linear expansion then the cooling that takes place after

6

deposition can create stress. Impurity introduction into the film can also cause stress. A model for the generation of internal stress in thin films is shown in Fig. 2.2. The film can shrink relative to the substrate as a result of surface tension forces (Fig. 2.2a). Misfit occurring during epitaxial growth can also cause this. Films containing tensile stress cause the substrate to bend concave upward (Fig. 2.2b) as it expands and the film contracts in an attempt to matchthe lattices of the film and substrate. Compressive stress in the film causes the opposite effect, i.e. the substrate bends convex outward.<sup>14</sup> In this last case, when the internal stress becomes too large, the thin films will peel off the substrate or even break the substrate for some substrate-material combinations.

Stress measurements can be performed by measuring the bending of the thin film by observing deflection of an optical beam, a process known as bulge testing. X-ray diffraction can also be used to determine lattice deformations. If the change in magnetic, electrical, or optical properties versus stress is well known then internal stress of a material may be measured indirectly by observing the change in these properties.<sup>14</sup>



a. Residual Tensile Stress b. Residual Compressive Stress Fig 2.2 Residual stresses and the effects on the film-substrate interface.

For this investigation a high pressure gas cell was chosen as a means of applying stress to the substrate. Two pressure cells were designed with window sizes of 1.4 cm and 4.9 mm. The results in this study were measured with the 1.4 cm window cell. By applying gas pressure to the back of the substrate the substrate bulged out and produced tensile isotropic in-plane stress in the thin film. Gasket material was used to seal the two halves of the cell together. The pressure cell was made out of brass so as to be nonmagnetic (see Fig. 2.3). Nonmagnetic screws (316 stainless steel) were used to fasten the two halves together.

Several different techniques of sealing the substrate in the pressure cell were attempted. For thin and thick glass substrates the best results were obtained by coating the inner front of the cell with vacuum grease. The substrate was then mounted directly to the inside of the cell (see Fig. 2.4a). This technique was also used to seal 0.4 mm thick



Fig. 2.3: Picture of pressure cell.

silicon substrates up against the back inside of the cell. For copper foils of 0.5mm and 0.1mm thickness, gasket material (1/16" thick compressed Armid sheet McMaster Carr



Fig. 2.4: Gasket strategy for (a) thin glass and 0.4 mm-thick silicon substrates, (b) thin and thick copper foil, (c) 0.7 mm thick silicon

Supply company part #9479K54) was placed in between the substrate and the front inside of the cell. To maintain a good seal against the pressure cell two rubber O-rings and one piece of gasket material were used to press the substrate up against the gasket material and the pressure cell (see Fig. 2.4c). A similar technique was used to seal the thicker 0.7 mm silicon substrates to the back of the pressure cell and is shown in Fig. 2.4b. Attempts to get a good seal with the thinner silicon and gasket material lead to substrate cracking or destruction.

To measure strain on the substrate a beam from a HeNe laser was reflected off the substrate and onto a white screen. The spot size of the beam was measured at the screen as the gas pressure in the cell was increased. The radius of curvature is computed from the increase of the spot size and used to calculate the strain:

$$R = \frac{2hd}{H-h}$$
[2.7],

where R is the radius of curvature, h is the beam diameter of the incident laser beam, and H is the diameter of the laser spot on the screen at a distance d away from the sample. The experimental setup is shown in Fig. 2.5.



Fig. 2.5: Experimental setup to determine the radius of curvature of the sample

The strain,  $\sigma_{s_1}$  is the ratio of the change in surface area over the relaxed surface area. The strain was calculated using the model shown in Fig. 2.1a. The film thickness

$$\sigma_{s} = \frac{\Delta S}{S} = \frac{4\pi R^{2} - 4\pi (R - \frac{1}{2}t_{s})^{2}}{4\pi R^{2}} = \frac{t_{s}}{R}, R >> t_{s}$$
[2.8]

was considered to be negligible with respect to the thickness of the substrate, t<sub>s</sub>.

An alternate model assumes the substrate expands like a balloon. The strain is then defined as the change in spherical surface area and is given by Eqn 2.9 (Fig. 2.1b).

$$\sigma_{r} = (1 - \sqrt{1 - r^{2}/R^{2}}) \frac{2R^{2}}{r^{2} - 1} \quad [2.9]$$

This model has to be used if the sample is glued in the pressure cell.

Three different types of substrates were examined for their strain properties: 0.2mm thick glass microscope slides, 0.5mm copper foil, 0.7mm silicon squares and 0.4mm silicon pieces. The glass substrates showed a maximum strain of 0.005 over the applied pressure range. The copper foil showed a strain of 0.004 and the 0.7mm silicon a strain of 0.0025. Thin glass microscope slides were chosen as substrates on which to sputter magnetic films. Figures 2.6 through 2.8 show the pressure strain relations for the different substrates. The largest strain could be obtained by the glass substrates. For the copper substrates the data measured while increasing the pressure clearly differs from that measured decreasing the pressure. The copper substrate clearly showed plastic deformation after the application of pressure. The limitations of the 4 different substrates are summarized in table 2.1.



Figure 2.6 NiFe on glass



Figure 2.7 Silicon substrate 0.7mm thick



Figure 2.8 Copper foil substrate

## Table 2.1 Substrate Limits

Substrate	Sealing	Max.	Max.	Limit	Regulator
Material	Technique	Strain	Pressure		
Glass	fig. 2.4a	0.005	80 psi	Breaking of	low
				Substrate	
thin Si	fig. 2.4b	0.0001	30-300 psi	Breaking of	high
			_	Substrate	
thick Si	fig. 2.4a	0.0025	25-30 psi	Breaking of	high
				Substrate	
Copper	fig. 2.4c	0.0035	500 psi	air leak	high
	_		_		

## **CHAPTER 3**

### FERROMAGNETIC AND MAGNETOELASTIC PROPERTIES

#### **3.1 Ferromagnetism**

Magnetism can be divided into the following types of materials: diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism, and ferrimagnetism. All materials are either diamagnetic or paramagnetic above a certain temperature in the presence of an applied magnetic field. A small class of paramagnetic materials will retain their magnetization below a critical temperature, T<sub>c</sub>, after removal of the applied field. These materials are referred to as ferromagnetic. Not only do these materials retain their magnetization after removal of an external field, the magnetic field produced by the material magnetization can be quite strong, exhibiting a thousand times greater effect



Figure 3.1. Hysteresis Curve: Magnetization vs. Applied Magnetic Field



Unmagnetized Sample Domain Wall Movement Rotation Reversal a) b) c) Figure 3.2. Magnetic Domains a) Unmagnetized substance, randomly oriented magnetic domains, b) Net magnetization due to external magnetic field and c) Saturation magnetization. <sup>15</sup>

than that observed in paramagnetic and diamagnetic materials. The hysteresis curve which is a graph of magnetization versus the applied magnetic field is characteristic of ferromagnetic materials and is shown in figure 3.1. This curve shows the change in magnetization, M, as the external magnetic field, H, is increased to a positive saturating field value, decreased to a negative saturating value and then returned to a positive saturating value. Each atom in a material maybe viewed as a tiny magnet (figure 3.2). Typically in a ferromagnet there will be groups of atoms called domains that all have their magnetic moments aligned parallel so the domain has a net magnetization. As the external field is increased more and more domains will tend to become aligned with the external. The magnetization will change by two different mechanisms, domain wall motion and magnetization reversal. Domain wall motion, i.e. the growth of the domains that are magnetized parallel to the applied field at a cost of the other domains will occur at low and moderate magnetic fields. At higher fields the magnetization will reverse by rotation of the magnetic moments. The value of the field that produces the saturation magnetization,  $M_s$ , is called the saturating field,  $H_s$ . The value of the magnetization when

15

the field is returned to zero is called the remanent magnetization, M<sub>r</sub>. The strength of the field necessary to reduce the magnetization to zero is called the coercive force, H<sub>c</sub> (see fig. 3.1). Early theories of magnetism were phenomenological laws such as the Curie-Weiss law. For a complete quantitative description of ferromagnetism, quantum mechanics is required. Molecular field theory was initially used and provides a conceptual framework based on the interaction of neighboring spins, but it does not predict which elements will be ferromagnetic or the magnitude of the magnetization . For the ferromagnetic metals such as iron, cobalt, and nickel, the overlap of the 3d and 4s orbitals along with the large density of states around the Fermi level allows for the effect of ferromagnetism. These electrons are the same as those responsible for electric conduction and thus the magnetic moment is not localized in these transition metals. In paramagnetic materials the applied field causes the magnetic moments to align with the magnetic field, but in ferromagnets this happens spontaneously. The exchange energy couples neighboring spins and produces a lower energy for parallel alignment.<sup>16</sup> Slater and Bethe calculated the exchange integral given in equation 3.1. A positive value of the exchange integral means that parallel spins are energetically favored over antiparallel. Thus the ferromagnetic metals Co, Ni, and Fe have a positive value. If the integral is negative, two neighboring spins will tend to be anti-parallel and the material will be antiferromagnetic and have no net magnetization, such as occurs in manganese and cromium.<sup>17</sup>

$$I_{ex} = \int \psi_{a}(1)\psi_{b}(2)\psi_{a}(2)\psi_{b}(1)\left[\frac{1}{r_{ab}} - \frac{1}{r_{a2}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}}\right]d\tau$$
[3.1]

16

Figure 3.3 gives the band structure for several of the transition metals. The orientation of the magnetic spins in the free nickel atoms is determined by Hund's rule (Fig. 3.3a). Because of the exchange interaction (Eqn. 3.1) the energy bands for spin up and spin down electrons are shifted with respect to each other. This causes a different occupation of both bands, particularly at low temperatures, and results in a net magnetic moment (see Figs. 3.3d,e, and f).<sup>18</sup>



Fig. 3.3 3d and 4s electron orbitals for ferromagnetic metals and copper.<sup>18</sup>

#### **3.2 Magnetic Anisotropy**

Magnetic properties often depend on the direction in which they are measured. This is referred to as magnetic anisotropy. There are several types of anisotropy that include the following: crystal anisotropy, shape anisotropy, stress anisotropy, induced anisotropy by magnetic annealing, plastic deformation, or irradiation, and exchange anisotropy.<sup>15</sup> Crystal anisotropy is intrinsic to the material, all others are extrinsic properties of the material and depend on the deposition method and conditions used and post-deposition treatment. There exists an easy axis in the crystal along which the magnetization prefers to align with and which will be the minimum energy state for the material. There also exists a direction in the crystal for which the anisotropy energy will be maximum and this is referred to as the hard axis.

If  $M_s$  points in a non-easy direction in the crystal then energy must be stored in the crystal, since work must be done against the crystalline anisotropy to move the magnetization vector away from the easy axis. This energy is called the crystal anisotropy energy. For a cubic structure, the anisotropy energy is given by

$$E = K_0 + K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2(\alpha_1^2 \alpha_2^2 \alpha_3^2) + \dots$$
[3.3]

where  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are the direction cosines of the magnetization vector with respect to the lattice structure.  $K_0$ ,  $K_1$ ,  $K_2$  are the anisotropy constants of the material expressed in units of J/m<sup>3</sup>.





Several types of electron-lattice interactions are important in magnetic materials. Spin-spin coupling is the exchange interaction that keeps neighboring spins parallel or antiparallel but is not coupled strongly to the lattice and thus does not contribute to the anisotropy. The orbit-lattice coupling is strong but the orbits change very little with change in applied field. This leaves spin-orbit coupling as the major contributor to the anisotropy energy. As the spin changes with the applied field the orbit also tries to reorient, so the anisotropy is the energy necessary to overcome the spin-orbit coupling. The direction of  $M_s$  is controlled by  $K_1$ .<sup>16</sup> Iron has a body-centered crystal (bcc) structure (fig. 3.4) with the easy axis in the 100 direction and the hard axis in the <111> direction and  $K_1=10x10^3$  J/m<sup>3</sup>. Nickel has a face-centered crystal (fcc) structure (fig. 3.5) with easy axis in the <111> direction and hard axis in the <100> direction and  $K_1=-4.5x10^3$  J/m<sup>3</sup>. The films used in this study have a concentration of 35% iron and thus will have a positive  $K_1=0.4x10^3$  J/m<sup>3</sup> A positive  $K_1$  corresponds to an easy axis along the <100> direction. Fig. 3.6 shows the dependence of the anisotropy energy on the percent composition of nickel-iron. Most sputtered films such as those produced for this study, will be in the disordered state. The production of the ordered state would require a long thermal annealing. From the phase diagram in Fig. 3.7, it can be concluded that below a 40% iron composition the alloy will have a fcc structure and phase similar to nickel. It is expected that Ni-Fe 35% has an fcc structure and a crystal anisotropy much smaller than that of pure nickel, with an easy axis along the 100 direction.



Fig 3.5 Anisotropy of the magnetization curves of nickel along the 3 major crystal axis. Kaya<sup>20</sup>



Fig 3.6 Compositional dependence of  $K_1$  anisotropy constant for ordered and disordered Ni-Fe alloys. Bozorth, Kagawa and Chikazumi <sup>20,21</sup>



Fig. 3.7 Phase diagram for Ni-Fe alloy,  $\alpha$  is bcc,  $\gamma$  is fcc,  $\theta$  is the  $T_c$  boundary. Bozorth  $^{18}$ 

#### **3.3 Magnetostriction**

When a material becomes ferromagnetic it undergoes a small change in size. This change is referred to as magnetostriction and is described by the strain parameter  $\lambda = \Delta l/l$ , where  $\Delta l/l$  is the fractional change in length. As a material cools through the Curie point magnetic domains form and an accompanying change in length occurs. This type of magnetostriction is referred to as spontaneous magnetostriction. The maximum strain,  $\lambda_s$ , is called the saturation magnetostriction and is equal to the maximum fractional change measured at M<sub>s</sub>. In between these two cases is the field-induced magnetostriction that varies as the externally applied field changes. If a magnetic field is applied perpendicular to the easy axis of a crystal and there is uniaxial anisotropy, the field-induced magnetostriction is given by <sup>16</sup>

$$\lambda = \frac{3}{2} \lambda_s \cos^2 \theta \qquad [3.4].$$

The physical basis of magnetostriction is shown in figure 3.8. The change in length is very small usually on the order of  $10^{-5}$  for the ferromagnetic metals although below room temperature it can be much larger for some rare earth metals due to the larger spin-orbit coupling. As spins in the material align to the external field, the spin-orbit coupling causes a reorientation of the orbits which leads to elongation of the crystal lattice in one or more directions. Magnetization data for polycrystalline materials is given in Table 3.1.


Fig 3.8 Effects of magnetostriction on atomic orbitals. Cullity<sup>16</sup>.

Table 3.1 Magnetostriction for Polycrystalline Materials. Cullity<sup>16</sup>.

Material	$\lambda_s$
Fe	-7x10 <sup>-6</sup>
Ni-Fe 35%	_
Ni	-34x10 <sup>-6</sup>

#### **3.4 Stress and Magnetic Properties**

A change of the magnetostriction causes a change in length (strain) in the material. Similarly, an applied stress will cause a change in the magnetization of the material. That mechanical stress can have a strong influence on magnetic properties is illustrated in figures 3.9, 3.10, and 3.11. These figures show some typical effects of stress on the hysteresis curve in case nickel, iron, and nickel-iron permalloy. Curves like these indicate that the effect of stress on magnetic properties is similar to the magnetostriction effect and stress effects are often referred to as inverse magnetostrictive effects.

An externally applied stress will cause a length change of the material, i.e. a strain as explained in chapter 2.

$$\sigma = \frac{\Delta l}{l}$$
 [3.5]

The strain, i.e. the change of the lattice constant will induce an extra anisotropy energy term

$$E_{stress} = -\frac{3}{2}\lambda_s \varepsilon \cos^2 \theta \qquad [3.6]$$

where  $\lambda_s$  is the saturation magnetostriction,  $\varepsilon$  is the applied stress, and  $\theta$  is the angle between the magnetization and the stress axis. This stress changes the effective anisotropy energy, Eqn. 3.3 and thus changes the hysteresis. Figures 3.12 and 3.13 demonstrate the effects of tensile and compressive stress respectively on a material with positive magnetostriction. In these figures *a* represents the un-stressed state with crystal anisotropy, while *b* and *c* show the effects of increasing strain, and *d* shows the influence of a magnetic field. It is clear that the stress can drastically change the anisotropy energy and thus create an easy axis parallel or perpendicular to the stress axis depending on the signs of  $\sigma$  and  $\lambda_s$ .



Fig. 3.9 Effect of tension on the magnetization of a material with positive magnetostriction. Cullity<sup>16</sup>.



Fig. 3.10 Effects of tensile (+8000 lb/in<sup>2</sup>) and compressive (-8000 lb/in<sup>2</sup>) stress on the magnetization of iron. Kuruzar <sup>23</sup>



Fig. 3.11 Effect of tensile stress on the magnetization of Permalloy 68. Bozorth<sup>18</sup>.







Fig. 3.13 Magnetization of a material with positive magnetostriction under compressive stress. Cullity<sup>16</sup>.

#### **3.5 Thin Films**

For thin films we can expect similarities with bulk materials down to thicknesses of 5000Å. Below a thickness of 5000Å the magneto-elastic properties change as the film becomes thinner. This change in thinner films leads to differences in the response to applied stress. The thinnest films, under 200Å, show an increase in coercivity with applied tensile stress, which is an opposite effect as observed in thicker films by Callegaro, et al.<sup>11,12</sup> Callegaro also found that the total stress state, including both the internal and external components, induces an inverse magnetostrictive anisotropy. For a material like nickel with negative magnetostriction and an applied tensile stress, a uniaxial anisotropy is created in the film plane. "This anisotropy is superimposed onto the shape anisotropy, which instead creates an easy plane of magnetization coincident with the film plane."<sup>12</sup> At a very high strains a transition to a perpendicular easy axis is expected, but is not observed at strains below the plastic limit of the materials, thus the observed anisotropies created are in-plane. The net observed effect is a reduction of the in-plane coercivity.<sup>12</sup> For the thicker films in this study the same effect on coercivity is expected.

#### **3.6 Applications**

Of the many applications for thin magnetic films, the most immediate use of the results presented in this study is in the fabrication of a device to measure stress. Such a device could be used in a force sensor, an accelerator sensor, or a pressure sensor.

A magnetic film with linear relationship between coercivity and applied stress can be used in a device to measure stress. If the permeability depends on stress then the stress in a sensor may be obtained by measuring either the inductance of the magnetic coil or the hysteresis loss in the coil. Given a semiconductor device constructed like figure 3.15 and modeled as in figure 3.14, 2 types of measurements can be made to determine the stress.

1.) Inductance measurements may be made by using either toroidal coil,

$$L = \frac{\mu N^2 h}{2\pi} \ln \frac{b}{a}$$
, infinite solenoid,  $L' = \mu n^2 S$ , or 2 coils wound on a straight cylindrical

coil, 
$$L_{12} = \frac{\mu}{l_1} N_1 N_2 S$$
 (Cheng<sup>24</sup>,1989).

2.) Another approach can use measurement of the hysteresis loss in the coil to determine stress. The hysteresis loss is the work needed to reverse the magnetization from positive to negative and back to positive and is linear proportional to the surface area of the hysteresis curve,  $W_h = \int \mu_0 H dM$ . An approximation for the power dissipated in the coil is given by the following equation

$$P_{hyst} = \frac{\omega}{12} \frac{L^2 I^2}{S^2 \mu} 25$$

where  $P_{hyst}$  is the energy dissipated in the coil per unit time,  $\mu$  the permeability, S the cross sectional area of the coil, I the current through out the coil, and  $\omega$  the angular

frequency(Dielectric<sup>25</sup>1977). If the sample can be saturated with a field large enough then  $W_h$  can be calculated. For a square hysteresis curve  $M_s$  is not expected to change much and  $W_h$  becomes linear proportional to the coercivity.  $W_h$  can then be calculated by measuring the AC resistance of the coil, i.e. the real part of the impedance.



Fig. 3.14 Induction measurements can be made with two coils.



# **CHAPTER 4**

# **MAGNETO-OPTICAL KERR EFFECT**

## 4.1 Polarized light.

Polarized light phenomena have been observed for over 300 years, but only in the last 180 years have satisfactory explanations been made . In fact only at the beginning of this century was the debate over whether or not light was a wave or particle settled - it is both, and its nature depends on the experiment performed. Silverman<sup>26</sup> and originally Wigner<sup>27</sup> point out that polarization is merely the spin state of light represented by either two linear components  $E_p$  and  $E_s$  or 2 circular components  $E_{rcp}$  and  $E_{lcp}$ .



Fig. 4.1 The definition of phase difference and amplitude ratio for linearly polarized light, circularly polarized light, and elliptically polarized light.

Polarized light, being anisotropic, lends itself well to the investigation of material properties. Upon reflection from or transmission through an anisotropic material the amplitude ratio of the two components and their phase difference can change. Fig. 4.1a shows the physical definitions of both parameters. Their mathematical description is given by phase difference  $=\delta_x - \delta_y$  and the amplitude ratio  $= \tan(\psi)$ . Together they determine the state of polarization (=SOP) of the light. If the angle  $\delta_x - \delta_y$  is an integral multiple of 180° then the light is linearly polarized (see Fig. 4.1 a). A phase difference of 90° or  $-90^\circ$  produces circularly polarized light in the case the amplitude ratio is 1 (see Fig. 4.1b). Other combinations of  $\delta_x - \delta_y$  and  $\tan(\psi)$  will in general give elliptically polarized light.

The electric field portion of the a linearly polarized light wave can be represented as a traveling transverse wave

$$\mathbf{E} = \operatorname{Real}\left(\hat{\mathbf{E}}_{o}e^{i(-\mathbf{k}\cdot\mathbf{r}+\omega t)}\right) = \operatorname{Real}\left(\begin{pmatrix}\hat{E}_{o}^{x}\\\hat{E}_{o}^{y}\end{pmatrix}e^{i(-\mathbf{k}\cdot\mathbf{r}+\omega t)}\right) = \operatorname{Real}\left(\begin{pmatrix}\tan(\psi)e^{i\delta_{x}}\\1e^{i\delta_{y}}\end{pmatrix}e^{i(-\mathbf{k}\cdot\mathbf{r}+\omega t)}\right)$$

$$(4.1)$$

where **k** is the wave vector,  $\omega$  is the angular frequency of the wave and  $\mathbf{E}_0$  is the complex amplitude vector of the wave. Its components,  $\mathbf{E}_o^x$  and  $\mathbf{E}_o^y$  describe the complex amplitudes of the components of the wave polarized along the x-direction and the ydirection. The vector formed by both components is called the Jones vector and describes unambiguously the state of polarization of the light beam.

#### 4.2 Ellipsometry

When polarized light is reflected from a material both the  $\delta_x$ - $\delta_y$  and tan( $\psi$ ) of the light beam are affected. The technique of measuring <u>the change of the amplitude ratio</u> (=tan( $\Psi$ )) and the <u>change in phase difference</u> (= $\Delta$ ) upon reflection is called ellipsometry (Fig. 4.2). By measuring these two parameters the various properties of the material may be computed such as dielectric constants, index of refraction, extinction coefficient, film thickness, and magnetic hysteresis curve (see section 4.4). Since ellipsometry measures a ratio and a phase difference it is a highly accurate and sensitive method of measuring material properties.<sup>28</sup>





Using Maxwell's equations and the boundary conditions forelectric and magnetic fields, it is possible to calculate the phase shift and amplitude change of the light beam upon reflection with a substance. The components of the electric field parallel to the plane of incidence are referred to as the p-components and the components of the electric field perpendicular to the plane of incidence as the s-components. The Fresnel reflection coefficients for the p and s-reflection are given by equations 4.2 and 4.3.

$$\hat{r}_{12}^{p} = \left| \hat{r}_{12}^{p} \right| e^{i\delta_{12}^{p}} = \frac{\hat{E}_{12r}^{p}}{\hat{E}_{12r}^{p}} = \frac{\hat{N}_{2}\cos\phi_{1} - \hat{N}_{1}\cos\phi_{2}}{\hat{N}_{2}\cos\phi_{1} + \hat{N}_{1}\cos\phi_{2}}$$

$$\tag{4.2}$$

$$\hat{r}_{12}^{s} = \left| \hat{r}_{12}^{s} \right| e^{i\delta_{12}^{s}} = \frac{\hat{E}_{12r}^{s}}{\hat{E}_{12r}^{s}} = \frac{\hat{N}_{1}\cos\phi_{1} - \hat{N}_{2}\cos\phi_{2}}{\hat{N}_{1}\cos\phi_{1} + \hat{N}_{2}\cos\phi_{2}}$$

$$\tag{4.3}$$

$$\widetilde{N}_1 \sin \phi_1 = \widetilde{N}_2 \sin \phi_2 \tag{4.4}$$

Variables  $\tilde{N}_1$  and  $\tilde{N}_2$  are the complex refraction indices of the ambient atmosphere and the material, and  $\phi_1$  is the angle of incidence and  $\phi_2$  gives the angle of refraction.  $\hat{E}^{p}_{121}$  is the complex amplitude of the p-component of the incident wave and  $\hat{E}^{p}_{12r}$  is the complex amplitude of the p-component of the reflected wave.  $\delta^{p}_{12}$  is the phase shift of the p-component of the interface between medium 1 and 2.  $|r^{p}_{12}|$  is the change in amplitude of the p-component of the wave upon reflection at the interface between medium 1 and 2.

If we know the SOP of the incident beam and we determine the SOP of the reflected beam it is possible to calculate the change of phase difference and amplitude ratio upon reflection and couple this to above given Fresnel equations:

$$\rho = \frac{\hat{r}_{12}^{p}}{\hat{r}_{12}^{s}} = \frac{\left|\hat{r}_{12}^{p}\right|}{\left|\hat{r}_{12}^{s}\right|} e^{i(\delta_{12}^{p} - \delta_{12}^{s})} = \tan(\Psi)e^{i\Delta}$$
[4.5]

 $\Delta$  and  $\Psi$  are the physical quantities measured in ellipsometry systems.

The most simple ellipsometer is a null ellipsometer. It consists of a light source (usually a monochromatic source such as a laser), a compensator (a  $\lambda/4$  plate), a polarizer, a second polarizer called an analyzer, and a detector. See figure 4.3 for a block diagram of a null-ellipsometer.

The angular convention is that all angles are measured as positive counterclockwise from the plane of incidence when looking into the beam. The compensator is positioned with its fast axis rotated at 45 degrees with respect to the plane



Fig. 4.3 Diagram of a null ellipsometer. The light reflected from the surface will become linear polarized when the polarizer is at the proper angle.

of incidence. The polarizer and compensator form a phase shifter that can introduce any arbitrary shift between the s and p-component of the light depending on the angle of the polarizer. The calculation is represented by the Jones calculus shown below. The phase shift introduced by those components just compensates for the phase shift introduced by reflection of the sample. So the light reflected from the sample is linearly polarized and can be nulled by the analyzer.

Conceptually we can understand the working of the phase shifter from Fig. 4.4. It shows elliptically polarized light. The major axis of the ellipse is somewhere at -45 degrees. This light can be described by two perpendicular components that are equal in amplitude



Fig. 4.4: The phase shift between two orthogonal components of elliptically polarized light depends on coordinate system.<sup>29</sup>

and 1/8 of a wavelength out of phase. The same light can be described by two orthogonal components, one lined up with the major axis of the ellipse and one lined up with the minor axis. Those two components are exactly a quarter wave out of phase with each other and are evidently not equal in amplitude. So any elliptically polarized light can be

converted into linearly polarized light by placing a quarter wave plate in the path and aligning the fast and slow axes with the appropriate axes of the ellipse.

The effect of various optical elements on the SOP of an electromagnetic-wave field can be calculated by using Jones calculus<sup>1</sup>. The SOP of a polarized light beam is completely described by a Jones vector which elements are the complex amplitude of the p and s-component of the light. Each optical component, i.e. polarizer, compensator, sample, and analyzer, will change the SOP of the light beam. The change of each optical component is described by a matrix. More details can be found in Nusbaum<sup>29</sup>. For the null ellipsometer the following matrices describe the various optical components.

$$\mathbf{E}_{i} = \begin{pmatrix} 1 \\ i \end{pmatrix} \qquad \mathbf{C} = \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \qquad \mathbf{P} = \begin{pmatrix} \cos^{2} P & \sin P \cos P \\ \sin P \cos P & \sin^{2} P \end{pmatrix}$$
$$\mathbf{S} = \begin{pmatrix} r_{p} & 0 \\ 0 & r_{s} \end{pmatrix} \rightarrow \begin{bmatrix} \tan(\Psi)e^{i\Delta} & 0 \\ 0 & 1 \end{bmatrix} \qquad \mathbf{A} = \begin{pmatrix} \cos^{2} A & \sin A \cos A \\ \sin A \cos A & \sin^{2} A \end{pmatrix} \qquad [4.6]$$
$$\mathbf{E}_{d} = \mathbf{A} \cdot \mathbf{S} \cdot \mathbf{C} \cdot \mathbf{P} \cdot \mathbf{E}_{i} = \mathbf{A} \cdot \mathbf{S} \cdot \begin{bmatrix} \cos(2P) + \sin(2P)i \\ i \end{bmatrix} = \mathbf{A} \cdot \begin{bmatrix} \tan \Psi e^{i\Delta} (\cos(2P) + \sin(2P)i \\ i \end{bmatrix}$$
[4.7]

The Jones vector in the middle represents light for which the s-component leads the pcomponent by  $\pi/2$ -2P. In other words the phase shift introduced by polarizer and quarter wave plate is  $\pi/2$ -2P. The Jones vector on the right represents linearly polarized light if:

$$\Delta + 2P = \frac{\pi}{2} \quad \text{or} \quad \Delta + 2P = \frac{3\pi}{2} \quad \text{and thus } \Delta = \frac{\pi}{2} - 2P_4 \quad \text{or} \quad \Delta = \frac{3\pi}{2} - 2P_2$$
$$\Delta + 2P = \frac{5\pi}{2} \quad \text{or} \quad \Delta + 2P = \frac{7\pi}{2} \quad \text{and thus } \Delta = \frac{5\pi}{2} - 2P_3 \quad \text{or} \quad \Delta = \frac{7\pi}{2} - 2P_1 \quad [4.8]$$

Assuming we measure P<sub>2</sub> and P<sub>3</sub> we can calculate D from:  

$$2\Delta = \frac{8\pi}{2} - 2(P_2 + P_3) \Leftrightarrow \Delta = 2\pi - (P_2 + P_3)$$
[4.9]

For P3 and P4 we find:

$$\mathbf{A} \cdot \begin{pmatrix} \tan \Psi \\ 1 \end{pmatrix} = \begin{pmatrix} \cos^2 A \tan \Psi + \sin A \cos A \\ \tan \Psi \sin A \cos A + \sin^2 A \end{pmatrix} = \vec{0}$$

$$(4.10)$$

$$\cos A \tan \Psi + \sin A = 0 \Leftrightarrow \tan \Psi = -\frac{\sin A}{\cos A} = -\tan A \Leftrightarrow \Psi = -A_4 \text{ or } \Psi = \pi - A_3$$

For P1 and P2 we find:

•

$$\mathbf{A} \cdot \begin{pmatrix} \tan \Psi \\ -1 \end{pmatrix} = \begin{pmatrix} \cos^2 A \tan \Psi - \sin A \cos A \\ \tan \Psi \sin A \cos A - \sin^2 A \end{pmatrix} = \vec{0}$$

$$(4.11)$$

$$\cos A \tan \Psi - \sin A = 0 \Leftrightarrow \tan \Psi = \frac{\sin A}{\cos A} = \tan A \Leftrightarrow \Psi = A_2 \text{ or } \Psi = \pi + A_1$$

Assuming we measure  $A_2$  and  $A_3$  we can calculate  $\Psi$  from :

$$2\Psi = A_2 + \pi - A_3 \Leftrightarrow \Psi = \frac{\pi - (A_3 - A_2)}{2}$$
[4.12]

To measure a large number of data points, such as spectra data across the visible spectrum, the null technique can be quite slow and other methods such as modulation techniques are preferred.

#### 4.3 Modulated Ellipsometry

Modulation of the polarized light wave can be accomplished by use of a photoelastic modulator (=PEM) to continuously and periodically vary the SOP of the incident light beam. The PEM is basically an electronic compensator. It is a crystal of fused silica in which a standing acoustic wave is generated by piezoelectric transducer. The periodic compressive and tensile stress will cause a periodic optical birefringence and associated with it a periodic retardation. This technique greatly speeds up data collection and provides excellent signal to noise ratio<sup>30</sup>. Although all components are available in the optical characterization laboratory, currently this setup is not used to do ellipsometric measurements on non-magnetic samples. More details on this technique can be found in Azam<sup>31</sup>. A possible setup is given in Fig. 4.5.



Fig. 4.5: Modulated Ellipsometry

#### 4.4 Magneto-Optical Kerr Tracer.

Ellipsometry can also be used to measure magnetic properties. Faraday in 1846 demonstrated that the plane of polarization of light transmitted through a magnetized material is rotated. With Faraday's work and observations of metallic reflection, Kerr in 1877 discovered that "a true south pole of polished iron, acting as a reflector, turns the plane of polarization righthandedly."<sup>32</sup> In honor of his work the parameters measured for



Fig. 4.6: Magneto-optic Kerr rotation and Kerr ellipticity.<sup>15</sup>

the change in polarization of light upon reflection from a surface are called Kerr rotation and Kerr ellipticity. The figure below shows what happens if we reflect linearly polarized light from magnetized material. The plane of polarization of the reflected wave will be slightly rotated and the reflected light wave will no longer be strictly linearly polarized. Those effects are referred to as the magneto optic Kerr rotation and the magneto optic Kerr ellipticity. The figure below shows the definition of the angles.

Depending on the orientation of the magnetization several modes of Kerr effect can be considered. If the magnetization is perpendicular to the surface of the film it is called the polar Kerr effect. Kerr rotation and Kerr ellipticity are maximum in this mode when the angle of incidence is zero degrees. For larger angles of incidence the measured effects are smaller. If the magnetization is in the plane of the film we can consider two types of Kerr effects, the longitudinal Kerr effect where the magnetization is in the plane of incidence and the transverse Kerr effect where the magnetization is perpendicular to the plane of incidence. For the longitudinal and transversal Kerr effect the Kerr effects are zero at perpendicular incidence and maximum for an angle of incidence between zero and ninety degrees depending on the material properties. The measurements presented in this thesis are all performed in the longitudinal mode. The Kerr rotation originates from the different phase shift that occurs for right circularly polarized (RCP) and left circularly polarized (LCP) light during reflection off a ferromagnetic material. The Kerr ellipticity originates from different absorption coefficients for RCP and LCP light when it reflects from ferromagnetic materials. The following relations are valid for small ellipticity values:

$$\varphi_k = -\frac{1}{2}\Delta_{cp} \quad \tan \varepsilon_k = \frac{\tan \Psi_{cp} - 1}{\tan \Psi_{cp} + 1} \quad , \qquad [4.13]$$

where  $\varphi_k$  is the direction of the major axis of the ellipse,  $\varepsilon_k$  is the ellipticity,  $\Delta_{cp}$  is the phase between the LCP and RCP components of the light, and  $\tan(\Psi_{cp})$  is the amplitude ratio of the RCP and LCP components of the light. If we examine Fig. 4.5 we see that light linearly polarized at 45 degrees with respect to the plane of incidence is falling on the PEM. The PEM will modulate this light between RCP and LCP. Figure 4.7 shows the principle of the measurement setup. In the case where the sample is not ferromagnetic and the reflection coefficients for RCP and LCP light are the same, the s-component of the light reflected from the sample (x-projection) will not show any intensity variation. When the sample is ferromagnetic and shows a Kerr rotation, the intensity after the analyzer will be varying at twice the modulation frequency. For the LCP and RCP states the intensity is the same as for the non-ferromagnetic case, but the intermediate linearly polarized states will clearly result in a larger intensity. Figure 4.7d shows the situation in the case the sample is ferromagnetic and shows a Kerr ellipticity. Now RCP and LCP light will be differently absorbed which will result in intensity variations with the modulation frequency. In summary, the Kerr rotation signal is contained in the  $2\omega$  signal and the Kerr ellipticity signal is contained in the  $1\omega$  signal.

A more rigorous treatment of the measurement technique can be performed by Jones matrices<sup>29,31</sup>. To describe the reflection of a ferromagnetic material we now use the Jones matrix in circular coordinates.  $r_{rcp}$  and  $r_{lcp}$  are the Fresnel reflection coefficients for RCP and LCP light at perpendicular incidence.

$$\mathbf{S} = \begin{bmatrix} r_{rcp} & 0\\ 0 & r_{lcp} \end{bmatrix} = \begin{bmatrix} \tan \Psi_{cp} e^{i\Delta_{cp}} & 0\\ 0 & 1 \end{bmatrix}$$
 [4.14]

As all the other Jones matrices will be in linear coordinates we need a matrix to convert linear coordinates, F, to circular coordinates and the inverse transformation as well:

$$\mathbf{F}^{-1} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & \iota \\ 1 & -\iota \end{bmatrix} \qquad \mathbf{F} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -\iota & \iota \end{bmatrix}$$
[4.15]

So for the total setup we get:

$$\mathbf{E}_{i} = \begin{pmatrix} 1\\ i \end{pmatrix} \qquad \mathbf{C} = \begin{pmatrix} e^{i\delta} & 0\\ 0 & 1 \end{pmatrix} \quad \text{with } \delta = \frac{\pi}{2}\sin(\omega t)$$
$$\mathbf{P} = \begin{pmatrix} \cos^{2}\frac{\pi}{4} & \sin\frac{\pi}{4}\cos\frac{\pi}{4}\\ \sin\frac{\pi}{4}\cos\frac{\pi}{4} & \sin^{2}\frac{\pi}{4} \end{pmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1\\ 1 & 1 \end{bmatrix} \qquad \mathbf{A} = \begin{pmatrix} \cos^{2}0 & \sin 0\cos 0\\ \sin 0\cos 0 & \sin^{2}0 \end{pmatrix} = \begin{bmatrix} 1 & 0\\ 0 & 0 \end{bmatrix}$$

$$\mathbf{E}_{d} = \mathbf{A} \cdot \mathbf{F}^{-1} \cdot \mathbf{S} \cdot \mathbf{F} \cdot \mathbf{C} \cdot \mathbf{P} \cdot \mathbf{E}_{i} = \frac{1}{\sqrt{8}} \begin{pmatrix} r_{RCP} \left( e^{i\delta} + i \right) + r_{LCP} \left( e^{i\delta} - i \right) \\ 0 \end{pmatrix}$$

$$I = \mathbf{E}_{d}^{*} \cdot \mathbf{E}_{d} = \frac{1}{4} |r_{LCP}|^{2} \left( 1 + \tan^{2} \Psi \left( 1 + \sin(\delta) - 2 \tan \Psi \sin \Delta \cos \delta - \sin \delta \right) \right)$$

$$[4.16]$$

$$[4.17]$$

Using Bessel functions for a linear series expansion of  $sin(\delta)$  and  $cos(\delta)$ :

$$I = I_{o} + I_{\omega} \sin(\omega t) + I_{2\omega} \cos(\omega t) + \dots =$$

$$\frac{1}{4} |r_{LCP}|^{2} \left( 1 + \tan^{2} \Psi - 2 \tan \Psi \sin \Delta \cdot J_{o} \left( \frac{\pi}{2} \right) + \left( -2J_{1} \left( \frac{\pi}{2} \right) + 2 \tan^{2} \Psi J_{1} \left( \frac{\pi}{2} \right) \right) \cdot \sin(\omega t) + \left( -4 \tan \Psi \sin \Delta J_{2} \left( \frac{\pi}{2} \right) \right) \cdot \cos(2\omega t) \right)$$

$$\left( -4 \tan \Psi \sin \Delta J_{2} \left( \frac{\pi}{2} \right) \right) \cdot \cos(2\omega t) \right)$$

$$[4.18]$$

For small angles the  $\omega$  and  $2\omega$  components of the AC signal measured at the detector can be related to the ellipsometric angles as follows

$$\frac{I_{\omega}}{I_0} = 2J_1 \left(\frac{\pi}{2}\right) \frac{\tan^2 \Psi - 1}{\tan^2 \Psi + 1}$$

$$\frac{I_{2\omega}}{I_0} = \frac{-4\tan\Psi\sin\Delta J_2 \left(\frac{\pi}{2}\right)}{\tan_2 \Psi + 1}$$
[4.19]
[4.20] <sup>31,33,34</sup>

From these equations and Eqn. 4.13 it is possible to calculate the Kerr rotation and Kerr ellipticity. As a first approximation Kerr rotation and Kerr ellipticity are linearly dependent on the  $\omega$  and  $2\omega$  components of the light intensity respectively (see also Fig. 4.7).



Fig. 4.7: Retardation (a), SOP of reflected beam, s-component of the reflected light, and intensity with no Kerr effect (b), with Kerr rotation (c), with Kerr ellipticity (d).<sup>33</sup>

## 4.5 Other Types of Ellipsometers

Other methods of modulation include the Rotating Polarizer (RPE or RAE) and Rotating Compensator (RCE). The rotating polarizer and analyzer techniques have higher data acquisition speeds than null ellipsometers. However, the design of a vibration free polarizer or analyzer presents significant challenges. Furthermore problems can occur because the monochromator is placed after the sample in RPE and white light illuminating the sample can polarize the optics<sup>28</sup>. Also the polarization in the source beam can affect sensitivity. The rotating compensator uses 2 static polarizers and a rotating quarter wave plate. These systems eliminate polarization sensitivity but have a much limited spectral range due to the compensator.<sup>28</sup>

## 4.6 Quantum Mechanics

A macroscopic or classical explanation of magneto-optical effects makes use of the Zee man effect and dispersion theory. In the normal Zee man effect the spectral lines of a gas split into three components when viewed in a direction transverse to an applied magnetic field. The three components consist of a undisclosed linearly polarized component parallel to the magnetic field, and two components displaced to either side of the first line that are linearly polarized perpendicular to the magnetic field.

# **CHAPTER 5**

# **EQUIPMENT SETUP**

## 5.1 Monochromatic and Spectroscopic Ellipsometer

The basic modulated ellipsometer setup is shown below in fig. 5.1. A future variation of this system uses a xenon arc lamp, lenses and monochromator instead of the laser for a spectroscopic ellipsometer system. These components for the spectroscopic system were also used for measuring absorption and transmission spectra of materials. The laser provides a faster setup time with fewer optical elements to align and is better suited for magnetometry. A rough outline of the equipment will be given here. For more details on monochromatic ellipsometry see the thesis of Charlie Watts<sup>15</sup>.



# Fig 5.1 Monochromatic Kerr Ellipsometer. The size of the pressure cell is exaggerated.

## 5.2 Polarizer and Analyzer

The polarizer and analyzer are Glan-Taylor polarizers from the Karl Lambrecht Company. These consist of two prisms of birefringent material, such as calcite, that are separated by an air gap. The slope of the prism is such that the s-component of the light is internally reflected and the p-component is transmitted. The extinction ratio of these polarizer is  $10^{-5}$  which is much better than Polaroid film. The spectral range of the polarizers is 215-2300 nm.



Fig 5.2 Birefringence of a polarizing filter, arrows represent  $E_p$  and circles  $E_s$ .

#### **5.3 Photoelastic Modulator**

The Photoelastic modulator used is a PEM-90 from Hinds Instruments. PEMs contain a rectangular piece of transparent material, fused silica, and a piezoelectric transducer that are attached to each other at their ends. Vibration of the transducer causes repeated expansion and compression of the optical material which exhibits birefringence



# Fig. 5.3 Modulation by the PEM<sup>37</sup>

proportional to the applied stress.<sup>3</sup> Fig. 3.3 demonstrates the effects of the modulation of the state of polarization if the incident light on the PEM is linearly polarized under 45° with respect to the axis of the PEM. The PEM vibrates with a frequency of 50kHz. Its spectral range is 200-900 nm. To avoid damaging the electronics, the <u>PEM should never</u> be turned on without first connecting the optical head and the electronic head by the blue cable.

#### 5.4 Quarter Wave Plate, Lenses, and Helium Neon Lasers

A Quarter wave plate produces a 90° phase difference between the components of the light that is polarized parallel to the easy axis and the component that is polarized perpendicular to the easy axis. This component is used to adjust the DC level of the signal. Because the laser beam is reflecting off the spherical surface of the sample the spot size of the beam on the detector will spread out on reflection and will need to be refocused by a plano-concave lens. A 150 mm focal length ultraviolet (UV) transparent lens is used. For the spectroscopy system initial work was done with available lenses that were not UV transparent, although a set of UV. transparent lenses has been acquired and will extend the spectral range down to 190nm for future work.

Two different HeNe lasers were used to illuminate the sample. Both lasers operate at a wavelength of 632.8 nm. The first was a Uniphase 155SL which exhibited a 2% drift

in intensity over 30 minutes as measured by C. Watts<sup>15</sup>. A Melles Griot stabilized 05-STP 901 laser was purchased and samples with smaller signals were measured. This laser can be operated in a frequency or intensity stabilized mode to prevent drift. The intensity stabilized mode was used.

#### 5.5 Photo-diode, Detection Electronics, Electromagnet, and Gaussmeter

A ThorLabs PDA55 was used as a photodetector for the reflected laser light. The silicon photodiode has a photosensitive area of 3.6x3.6 mm. The peak spectral response is 0.6 A/W at 960 nm and a >0.3 A/W responsivity from 500 nm to 1025 nm. The detector may be used for detecting DC intensity or AC intensity to 10 MHz. The detector can source a 50  $\Omega$  load impedance up to 5 V. A beam intensity of 10 mW/cm<sup>2</sup> on the detector should not be exceeded.

To measure the AC and DC signals a lock-in amplifier and digital multimeter (DMM) are interfaced to a PC system with LabWindows software. The signal from the photo detector and the reference signal from the PEM controller provide the input to the lock-in amplifier. The DMM provides the DC intensity of the signal. Either the 50 kHz or 100 kHz component can be selected for measurement allowing the value of Kerr rotation or Kerr ellipticity to be determined respectively.

The electromagnet is made by Cenco and is capable of producing fields up to 700 Gauss. A Magnetic Instrumentation 912 Gaussmeter is used to measure the magnetic field at the sample. The Gaussmeter uses a Hall-effect probe to measure the applied field.

#### 5.6 Xenon Arc Lamp

An Oriel Xenon arc lamp , model 6140, with an ozone free bulb, #6370, was used as a full spectrum light source. With the 6370 bulb a spectrum from 250nm to 900nm could be obtained (see appendix 2). An ozone blower is attached to the lamp to cool the bulb and blow off any ozone produced by the current bulb or future UV producing bulbs. UV-opaque glasses are still worn when using the xenon lamp due to some emission from 250nm to 300 nm. These glasses also help cut down the intense glare. <u>Care must be</u> taken with any items within a foot or two of the lamp to avoid damage or fire due to the high heat output. The cables leading from the power supply to the arc lamp must be well insulated and contact with the cables should be avoided <u>especially during ignition</u> when a 10-20 kV voltage is applied across the lamp cathode and anode. The alignment procedure for the parabolic mirror behind the arc lamp bulb, as detailed in the Oriel manual, was followed to adjust the reflection of the cathode bright spot onto the condenser lens assembly.

#### **5.7 Monochromator**

A SpectraPro 300i imaging monochromator from Acton Research Corporation is used to select specific wavelengths of light from the xenon arc lamp. It has an imaging Czerny-Turner design with original polished aspheric mirrors used for the imaging capabilities. The monochromator has a 30 cm focal length and a grating with 1200 grooves/mm. The spectral range is 0-1400nm and a resolution of 0.1 nm at 435.8 nm. The focal plane extends 25 mm beyond the instrument housing. The entrance and exit

51

slits may be adjusted from 10 µm to 3 mm wide. Two problems were found with the particular unit used. First, possibly due to a software bug, the monochromator would not properly initialize and the selected wavelength would be wrong. Calibration with a known source such as a mercury or sodium vapor lamp should be done. <u>UV protection</u> goggles should be worn when working with sources which emit radiation in the UV to avoid permanent damage to the eyes. The second problem encountered was a drop in intensity and intensity non-uniformity during and immediately following a filter change. Changes have been made in the software<sup>34</sup> to adjust for these problems.

### **5.8** Photomultiplier Tube

A Hamamatsu 928 photomultiplier tube (PMT) was used as a detector for reflected light too low in intensity to be detected by the photodiode. The PMT high voltage is provided by a Hamamatsu C4900 Power Supply unit. The C4900 requires a input of +15 and -15 volts and a control voltage of 0-5 VDC. The control voltage produces a linear output for the PMT of 0 to -1250 VDC. A small circuit was built to provide the DC voltages to the C4900. Voltage regulator chips, LM7815 and LM7915, provide the  $\pm 15$ VDC and a potentiometer provides a user adjusted 0-5VDC for spectroscopy. For Kerr measurements a constant output voltage from the PMT is needed and an op-amp feedback control circuit is used to automatically adjust the high voltage of the C4900. Appendix 3 contains detailed schematics and information about the PMT electronics.

# **CHAPTER 6**

# SAMPLE PREPARATION

Nickel and nickel iron films were created with a DC magnetron sputtering system. Some of the interior parts are shown in Fig. 6.1. This sputtering system is a type of physical vapor deposition. By use of a potential difference between the targetand the substrate holder a momentum transfer process is created by which atoms are freed from the target by ions in a plasma and accelerated toward the substrate holder where they deposit onto the sample. The plasma is sustained by the high voltage ionizing the atoms of the controlled gas flow into the high vacuum chamber that encloses the entire system. Almost any conducting material can be sputtered in this manner. Thin film properties and growth rate can be controlled by adjusting the current and voltage applied between the target and substrate holder and sputtering gas flow.

Circular glass microscope slides and round cut copper foils were used as substrates. The substrates were all 4 mm in diameter. The glass samples were 1mm thick and the copper samples were 0.1 mm thick. The substrates were cleaned in an ultrasonic bath with micro 2% soap then rinsed in deionized water. This was followed with an ultrasonic bath of acetone, and then the samples were rinsed in isopropyl alcohol (lack of agreement). The nickel and nickel iron targets to be sputtered were cleaned in the same manner as the substrates. The titanium target was already installed in the

53

system. The magnet in gun 3 was changed to a stronger magnet to increase ionization for the magnetic target. The bell jar, substrate holders, and baffle are cleaned with Chem-Wipes and isopropyl alcohol. Appendix 1 lists the various parameters used in sputtering the nickel and nickel iron films. Film thicknesses are shown in Table 6.1. Sputtering conditions used by Watts<sup>15</sup> were repeated and his deposition rates of 0.2 Å /s for Ti, and 2 Å/s for Ni and NiFe 35% were used for calculation of the film thicknesses. Attempts to sputter different compositions of nickel iron failed. NiFe alloy with iron compositions of 45%, and 35%, were chosen as target materials. Both targets would not produce a plasma initially. By using the lathe in the physics machine shop the thickness of the target discs was reduced. By reducing target thickness it was expected that the corresponding increase of magnetic flux lines through the target would increase ionization above the target and a plasma would form. For the NiFe 35% a plasma was sustained and films were sputtered. After two successive thickness reductions (approximately 2mm) with the lathe the 45% permalloy targets would not produce a plasma. A previously used nickel target was then tried and successfully sputtered.

Two 20-30Å layers of titanium were sputtered onto the substrates. A seed layer was first deposited to aid in adhesion of the magnetic films. After the Ni or NiFe was deposited a titanium cap layer was sputtered on top to prevent oxidation of the magnetic film. The cap layer is thin enough to be practically transparent and thus contribute little to the measured signal.

The glass substrates break very easily. Placing or removing them from the substrate holders or pressure cell must be done with care. Removing a sample from the pressure cell is done by soaking the cell in acetone to dissolve the vacuum grease and

54

then rinsing the sample in isopropyl. Some peeling of the films off the substrate has been observed on broken substrates after cleaning.



Sputtering System Components

Patrick Holland Southwest Texas State University

Fig 6.1 Interior components of the TorayDC magnetron sputtering system.

Sample Date and		Nickel
Number	Thickness	Composition
021700-1	500nm	65%
021700-2	100nm	65%
021700-3	500nm	65%
021700-4	100nm	65%
022000-1	500nm	100%
002000-2	500nm	100%
022000-2	100nm	100%
002000-3	500nm	100%

# Table 6.1 Sputtered Samples

•

# **CHAPTER 7**

# RESULTS

## 7.1 Aluminum Oxide Iron Matrix

The first samples to be measured were created at the University of Florida at Tallahassee. They were made up of 9 layers each of 31.25Å of iron and 28Å of Al<sub>2</sub>O<sub>3</sub> on top of 80Å of Al<sub>2</sub>O<sub>3</sub> on silicon. The substrates for these samples were irregularly shaped pieces of silicon roughly 1 cm x 1 cm in area. Vacuum grease was coated on the interior front of the pressure cell and the silicon was pressed up against the greased surface. Kerr hysteresis curves were acquired at 4 pressure values as shown in Fig. 7.1. The data shows little or no effect of pressure on the hysteresis curves as seen from these films. A slight increase in coercivity may exist, but more data is needed to verify this fact.



Fig. 7.1 Kerr hysteresis curves at different pressures for a matrix of  $FeAl_2O_3$  on  $SiAl_2O_3$ 

## 7.2 Thick NiFe35% Films (500 nm)

The glass substrates with the NiFe films were placed directly against the greased inside of the pressure cell. Results for 500 nm films of NiFe35% shown in figures 7.2 and 7.3 indicate a dependence of coercivity on applied gas pressure. This effect is repeated on different samples and appears to be linear as shown in figure 7.5. The first HeNe laser used was found to have an intensity drift (C Watts). Improved measurements with an intensity regulated HeNe laser reinforce the previous results (fig. 7.3 and 7.4) and from 0-20 psi show coercivity to be linearly dependent on the applied pressure (fig. 7.5). Vacuum grease was cleaned off the samples with acetone and isopropyl alcohol after removal from the pressure cell. Figs. 7.5 and 7.6 show hysteresis curves of samples that have been cleaned and measured again. It can be seen that this cleaning procedure doesn't leave a residue on the film that affects the measurement.



Fig. 7.2 Hysteresis curves of 500nm of NiFe35% measured with standard HeNe laser.


Fig. 7.3 Hysteresis curves of 500nm of NiFe35% measured with intensity regulated HeNe laser.



Fig. 7.4 Kerr hysteresis curves of a NiFe35% sample that has been removed from the pressure cell, cleaned of grease, remounted in the pressure cell and measured



Fig. 7.5 Coercivity versus pressure for NiFe35%



Fig. 7.6 Kerr hysteresis curves of a NiFe35% sample that has been removed from the pressure cell, cleaned of grease, remounted in the pressure cell and measured again.



Fig 7.7 Repeat measurement of the same sample as shown in fig. 7.6.

## 7.3 Thin Films (100 nm)

The 100 nm thickness films showed no obvious change in coercivity with applied pressure. Initially the smaller signal made it difficult to obtain data with good signal to noise ratio as seen in fig. 7.8. With the intensity regulated laser the signal-to-noise ratio was improved (Figs. 7.9 and 7.10), but there was still no apparent dependency of coercivity (Fig. 7.11) on applied pressure.



Fig. 7.8 Kerr hysteresis curves of 100nm of NiFe35% measured with a standard HeNe laser.



Fig 7.9 Kerr Hysteresis curves of 100nm of NiFe35% measured with a intensity regulated HeNe laser.



Fig. 7.10 Re-measurement Kerr hysteresis curves of 100nm of NiFe35% measured with a intensity regulated laser.



Fig. 7.11 Coercivity versus pressure for 100nm film of NiFe35%

### 7.4 Stress Dependence Measured through Glass Substrate

The sample was inserted in the pressure cell backward to look for differences between the top and bottom of the film. Often when the optics were misaligned a DC intensity drift was seen. Both attempts (fig 7.12) to measure the backside of the sample produced hysteresis curves that did not close, possibly due to intensity drift. It is also possible that beam interference in the glass slide contributed to the drift. The coercivity is graphed in figure 7.13 and did not show much change.



Fig. 7.12 Kerr hysteresis curves with the substrate inserted backwards in the pressure cell.

## 7.5 Summary

Figure 7.14 shows the coercivities of the normal 500 nm thickness sample, the 100 nm sample, and the 500 nm sample measured backward from the substrate. The 100 nm and backward 500 nm samples show a slight increase in the coercivity and investigation at higher pressures is warranted but with the current data this cannot be confirmed within our current experimental error. The aluminum-iron matrix samples also need further investigation to determine if an increase in coercivity occurs or if the observed changes are merely part of the background noise. These latter samples should also be tested at higher pressures. Not all substrates of a particular material withstood



Fig. 7.13 Coercivity versus pressure with the substrate backwards.

equal pressure. One glass slide would break at 20 psi another would withstand pressures up to 45 psi. Repeated measurements of a sample seemed to increase the chances of breakage at lower pressures. It is possible that future measurements with the samples used might be made at higher pressures.



Fig. 7.14 Comparison of the coercivity of the 3 types of sample measured with increasing pressure.

## **CHAPTER 8**

## CONCLUSION

#### 8.1 Summary

Mechanical stress can have a large effect on magnetic properties of materials. This will prove useful in tailoring devices with specific magnetic properties such as stress sensors, magnetic memories, magnetic media, or micro-mechanical devices. Investigating one method of applying stress to magnetic films was the object of this study. A relation between applied stress (resulting strain) and the hysteresis curve were determined. The effect of film thickness and layering were examined.

A nickel iron alloy with 35% composition iron was chosen as the material for study. Films of two thicknesses were deposited on glass microscope slides with a DC magnetron sputtering system. The two thicknesses were 100 nm and 500 nm. The 500 nm thick films showed a definite decrease in coercivity with increasing applied pressure that appeared to be a linear relation. When these films were placed in the pressure cell backwards so the laser beam first passed through the glass substrate before reflecting off the film, there was no longer an observed change in coercivity with increasing pressure. This is a possible indication that the top and bottom of the films are of a different structure. Another possibility would be that the behavior for compressive stress is different than that for tensile stress. The 100 nm films exhibited no change in coercivity with change in pressure. These results indicate a possible change from bulk like properties for the 500 nm film to thin film properties as observed in the 100 nm

68

films. This might indicate different reversal mechanisms for the 100nm and 500nm thick films. (Sablik<sup>35</sup>)

## 8.2 Recommendations for future study

The first recommendation for future study is the examination of different compositions of NiFe alloys as well as other materials. Does stress effect all materials equally? An examination of a wider range of thicknesses to observe the transition to thin film properties should be carried out. The spectroscopic system should replace the laser for examination of wavelength related properties. It is also recommended that measurement of the film at different angles be carried out to measure magnetic anisotropy.

## SPUTTERING PARAMETERS

Date	;						Background Pressure							
2/15	/00	Lo	aded Sam	oles and t	argets									
2/16	/00	Re	load Targe	ets										
2/17	/00	Sp	utter				$8 \times 10^{-7}$	Т						
Gun	#		Material	Gun Ty	ype	Pov	wer	T	arget	Condit	ioning			
1			Ti	normal	normal		Dx1K	U	Jltraso	onic ace	etone, isopropyl,			
								p	respu	tter 100	W 20min			
2			NiFe 35%	magnet	tron	MI	<b>D</b> x500	U	Iltrase	onic ace	ctone, isopropyl,			
								p	respu	tter 100	W 20min			
3			NiFe 19%	magnet	tron	M	Dx500	l	Iltrase	onic ace	tone, isopropyl			
				<u></u>										
Subs	strate	S			Cleani	ng								
1	Glas	s C	Circular Sli	de x2	Ultrase	onic	with m	icro	,	therma	ll flash to 350 °C			
	<u></u>			1 0	aceton	e, 15	opropyl	•						
2	Glas	s C	fircular Sli	de x2	Ultrasc	onic	with m	1cro	,	therma	I flash to 350 °C			
2	Clas	- (		aceton	e, 15	opropyi			41	1.0-1.4-250.00				
3	Glas	s C	Ircular 511	de x2	Ultrasc		with m	icro	thermal flash to 350 °C					
4	Clas		Vincular Cli	do v2	Liltroge	$\frac{1}{1}$	opropyi	iono	no heater on #4					
4	Glass Circular Slide x2				oltrasonic with micro,					no nea	ter on #4			
Sub	Targ	et	Sputter P	Sputter P gas/flow		Sub T P		T	 I	l Rate	time			
Bub	Img	υı	mTorr	sccm	°C	W	v	A		A/s				
3	1		4	6.01	38	28	317	1		).3	1m6s			
3	2		4	6.02	38	89	407	0.2	22 3	}	27m50s			
3	1		4	6.02	40	28	316			).3	1m6s			
					_									
1	1		4	6.02	38	28	316			).3	1m6s			
1	2		4	6.02	38	89	404	0.2	2 3	;	27m50s			
1	1		4	6.03	40	28	317		0	).3	1m6s			
2	1		4	6.03	36	28	316		0	).3	1m6s			
2	2		4	6.03	37	89	412	0.2	18 3	;	5m33s			
2	1		4	6.03	37	28	317		C	).3	1m6s			
4	1		4	6.03	38	28	317		0	).3	1m6s			
4	2		4	6.03	38	89	410	0.2	17 3	;	5m33s			
4	1		4	6.03	40	28	317		0	).3	1m6s			
Thro	ottle c	n f	for all targe	ets										

**Table A1.1 Nickel-Iron Sample Preparation** 

Date						-	Background Pressure						
2/18	/00	Lo	aded Sam	ples and t	argets								
2/19	/00	Re	load Targ	ets									
2/20	/00	Sp	utter				4x	10-7	Т				
Gun	#		Material	Gun Ty	ype	Pow	ver		Targ	et Cor	nditioning	5	
1			Ti	normal		MD	<b>x</b> 1	Κ	Ultra	sonic	acetone,	isopropyl,	
									presp	outter	50W 5mi	n	
2				magnet	tron	MD	x5	00	Ultra	sonic	acetone,	isopropyl,	
									presp	outter	100W 10	min	
3			Ni	magne	tron	MD	)x5	00	Ultra	sonic	acetone,	isopropyl	
Subs	strate	S			Cleani	ng							
1	Glas	s C	Circular Sl	ide x2	Ultrase	onic v	wit	th mi	cro,	the	rmal flasł	n to 350 °C	
	~!				aceton	e, isc	<u>ppr</u>	opyl					
2	Glas	s C	Sircular SI	ide x2	Ultrase	onic v	wit	th mi	cro,	the	rmal flash	n to 350 °C	
	01		<u>, 1 01</u>	1 0	aceton	$\frac{e, 1SC}{\cdot}$	opr	opyl			1 (1 1	1 250.00	
3	Glas	s C	Sircular SI	ide x2	Ultrase	onic v	W11	th mi	cro,	the	thermal flash to 350 °C		
	0		0 1 1		acetone, isopropyl						1 // // // // // // // // // // // // //		
4	Cop	per	foil disc 2	κ2	Ultrasonic with micro,						no neater on #4		
					aceton	e, 1sc	opr	оруг					
Cul	Tana	at	Courte on D	and flow	Cul T	D		X7	T	Data		Threattle	
Sub	rarg	el	Spuller P	gas/110w				v V	1	Kale A/a	ume	Throthe	
1		1	5	6 02	42	~	70	v 219	A 0.088	A/S	1m6s	off	
1		2	75	6.02	41	2	20	320	0.088	0.5	27m50s	on	
1		1	1.5	6.08	41		20	318	0.277	03	1m6s	off	
		1		0.00		2	20	510	0.004	0.5	11105		
4		1		6.09	36		28	318	0.084	03	1m6s	off	
4		3	7	6.04	38	8	20	319	0.004	3	27m50s	on	
4		1	4	6.04	39		28	317	0.084	03	1m6s	off	
<b>·</b>		-		0.01	55			517	0.001	0.5	THIOD		
2		1	4	6.09	38		28	318	0.084	03	1m6s	off	
2		3		6.03	38		29	320	0 277	3	27m50s	on	
2		1	4	6.03	38		28	318	0.084	0.3	1m6s	off	
		-						210	0.001				
3		1	4	6.04	37	7	28	317	0.84	0.3	1m6s	off	
3		3	7	6.04	37		39	320	0.277	3	5m33s	on	
3		1	4	6.04	37		28	318	0.084	03	1m6s	off	
Ti o	ın let	ft o	n at 28W	during Ni	sputter	ing t	10 2	act as	gettere	er nun	nn	1	
					Spatter				0	<u>- p</u> un	<u>r</u>		

**Table A1.2 Nickel Sample Preparation** 

## SPECTROSCOPY SYSTEM



Monochromator Sample

Fig A2.1 Equipment setup for measuring absorption spectra.

lens	Focal Length	Diameter
	(cm)	(cm)
1	8	4
2	8	4
3	2.5	2.5
4	not used	not used

**Table A2.1 Lens Focal Lengths and Diameters** 

Fig A2.1 illustrates the arrangement of the equipment for measuring absorption spectra. Table A2.1 lists the diameters and focal lengths of the lenses used. Lens 4 was used in later setups and along with a fifth lens would be needed to form a small

collimated beam for measurement of small samples. This system will be used to replace the HeNe laser to form a spectroscopic Kerr ellipsometer.

For each measurement session a baseline spectrum of the xenon arc lamp was taken before mounting the sample in between the monochromator and the PMT. At the peak visible intensity of the xenon spectrum the PMT is adjusted to keep its output voltage below 1 volt. This same setting is then used throughout the session. Figs. A2.2 and A2.13 show the emission spectrum and percent transmittance of the xenon arc lamp. Figures A2.3 - A2.12 show the absorption spectra of various safety goggles and an inexpensive pair of sunglasses. Figs. A2.14-A2.21 show the absorption spectra and percent transmittance of two different blue absorbing filter films considered for filtering overhead room lights above a lithography system.



Fig A2.2 Emission spectrum of xenon arc lamp.



Fig A2.3 Absorption spectrum of standard lab safety glasses.



Fig A2.4 Transmittance of standard lab safety glasses.



Fig A2.5 Absorption spectrum of UV-protection glasses.



Fig. A2.6 Transmittance of UV-protection glasses.







Fig A2.8 Transmittance of Polaroid sunglasses.



Fig. A2.9 Absorption spectrum of Ar laser UV-protection goggles.



Fig A2.10 Transmittance of Ar laser UV-protection goggles.



Fig. 2.11 Absorption spectrum of UV-protection goggles.



Fig A2.12 Transmittance of UV-protection goggles.



Fig. A2.13 Emission spectrum of xenon arc lamp.



Fig. A2.14 Absorption spectrum of 1 sheet of bilavered filter film.



Fig A2.15 Transmittance of 1 sheet of bilayered filter film.



Fig A2.16 Absorption spectrum of 2 sheet of bilayered filter film.



Fig A2.17 Transmittance of 2 sheet of bilayered filter film.



Fig. A2.18 Absorption spectrum of 4 sheet of bilayered filter film.



Fig. A2.19 Transmittance of 4 sheet of bilayered filter film.



Sample\_Info Monoayer x1 -126 vdc



Fig A2.21 Transmittance of 1 sheet of monolayered filter film.

## **PHOTOMULTIPLIER ELECTRONICS**

A voltage regulator circuit was constructed to provide ±15 volts to the Hamamatsu high voltage regulator and PMT base holder, which in turn controls the gain of the PMT. The potentiometer allows the voltage supply to the PMT base to be adjusted from 0 to -1250V. <u>Caution must be exercised when working with high voltage</u>. For automatic control of the PMT gain another circuit was built to replace the potentiometer. This second circuit used two operational amplifiers to monitor the PMT signal out using a negative feedback loop to control the high voltage adjustment of the HV regulator. For more details on either circuit please see the PMT power supply manual by Jett Hendrix in the SWT optical characterization laboratory.



## **EQUIPMENT SPECIFICATIONS**

- 1. Filter Wheel<sup>39</sup>

- Photomultiplier Tube<sup>42</sup>
  Glan-Taylor Ultra-Violet Prism<sup>43</sup>
  450 Watt Xenon Arc Lamp Bulb<sup>41</sup>
  Photodiode<sup>44</sup>

HCTON Kesearch Lorp.

978-263-5086

# RC

## Filter Wheel Assemblies

#### Filter Wheel Assemblics:

ARC filter wheel assemblies are designed to hold up to six (6) 1.0" (25.4mm) diameter samples or filters. Normally up to five filters are installed with the sixth position left open. FA-448 filters wheels are available with manual or motorized filter selection.

**FA-448:** Manual version which includes a 2-pole stepping motor with integrated filter selection knob as shown in the photograph at right. To select a filter, the user simply rotates the knob. Manual FA-448 filter wheels are easily converted at any time for motorized operation by purchasing the Model FA-448-4 controller.

**FA-448-2:** Motorized FA-448 filter wheel includes a stepping motor plus FA-448-4 controller with RS232 computer interface and integrated thumb-wheel for filter selection. This assembly permits computer selection of filters, or motorized selection using the thumb-wheel control.



Normal

#### Second Order Radiation:

Diffraction gratings produce multiple orders of diffracted light where constructive interference permits light of one wavelength to appear at more than one angle of diffraction.

For example, 200nm light passing through a monochromator normally appears as 200nm "first order" light. Some of this 200nm light will also appear at 400nm as second order light. If the detector is sensitive to 200nm and 400nm wavelengths. It will detect both wavelengths simultaneously when the monochromator is tuned to a wavelength of 400nm.

This superposition of wavelengths can lead to ambiguous spectral data because the detector cannot normally distinguish between light of either wavelength. It must be prevented by using suitable "order sorting" filters.



ARC offers an order sorting filter set designed to eliminate unwanted second order radiation. The set consists of cut-off filters at 320nm, 590nm, 665nm, and 715nm. Typical transmission characteristics for these filters is shown in the graph at right.

#### How Order Sorting Filters Work:

Assume you plan to work at a wavelength of 400nm and wish to block second order 200nm light that is contaminating the data. Using the FA-448-1 or FA-448-3 order sorting filter wheels, you would index the 320nm cut-off filter into the beam path. This filter blocks 200nm while transmitting 400nm. allowing only the desired light to reach the detector. The unwanted light is eliminated for improved accuracy.







HAMAMATSU

PHOTOMULTIPLIER TUBES R928, R955

# Extended Red, High Sensitivity, Multialkali Photocathode 28mm (1-1/8 Inch) Diameter, 9-Stage, Side-On

#### FEATURES

Wide Spectral Response	
R928	185 to 900 nm
R955	160 to 900 nm
High Cathode Sensitivity	8
Luminous	250 μ A/Im
Radiant at 400nm	74mA/W
High Anode Sensitivity (at 1000V)	
Luminous	
Radiant at 400nm	
Low Drift and Hysteresis	

The R928 and R955 feature extremely high quantum efficiency, high current amplification, good S/N ratio and wide spectral response fromUV to near infrared. The R928 employs a UV glass envelope and the R955 has a fused silica envelope for UV sensitivity extension.

The R928 and R955 are well suited for use in broad-band spectrophotometers, atomic absorption spectrophotometers, emission spectrophotometers and other precision photometric instruments.



#### GENERAL

Parameter	Description/Value	Uni
Spectral Response		
R928	185 to 900	nm
R955	160 to 900	nm
Wavelength of Maximum Response	400	nm
Photocathode		
Material	Multialkali	-
Minimum Effective Area	8×24	mm
Window Material		
R928	UV glass	-
R955	Fused silica	
Dynode		
Secondary Emitting Surface	Multialkali	-
Structure	Circular-cage	-
Number of Stages	9	_
Direct Interelectrode Capacitances		
Anode to Last Dynode	Approx. 4	pF
Anode to All Other Electrodes	Approx. 6	pF
Base	11-pin base	_
	JEDEC No. B11-88	
Weight	Approx. 45	g
Suitable Socket	E678-11A (option)	-
Suitable Socket Assembly	E717-21 (option)	





Subject to local technical requirements and regulations, availability of products included in this promotional material may vary. Please consult with our sales office information furnished by HAMAMATSU is believed to be reliable. However, no responsibility is assumed for possible inaccuracies or ommissions. Specifications are subject to change without notice. No patent right are granted to any of the circuits described herein. © 1997 Hamamatsu Photonics K.K.

## PHOTOMULTIPLIER TUBES R928, R955

#### MAXIMUM RATINGS (Absolute Maximum Values)

Parameter	Value	Unit
Supply Voltage		
Between Anode and Cathode	1250	Vdc
Between Anode and Last Dynode	250	Vdc
Average Anode Current	0.1	mA
Ambient Temperature	-80 to +50	r

#### CHARACTERISTICS (at 25℃)

Parameter	Min.	R928 Typ.	Max.	Min.	R955 Typ.	Max.	Unit
Cathode Sensitivity Quantum Efficiency at Peak Wavelength	-	25.4 (at 260nm)	_	-	29.0 (at 220nm)	_	%
Luminous <sup>B</sup>	140	250	_	140	250		μA/Im
Radiant at 194nm	_	18	-	_	43		mA/W
254nm	_	52	_	—	56	_	mA/W
400nm	_	74	-	—	74	_	mA/W
633nm		41			41	_	mA/W
852nm	_	3.5	_	_	3.5		mA/W
Red/White Ratio C	0.2	0.3	_	0.2	0.3		
Blue <sup>o</sup>	—	8	_	—	8	_	μ A/Im-b
Anode Sensitivity							
Luminous <sup>E</sup>	400	2500	-	400	2500	_	A/Im
Radiant at 194nm	-	1.8 × 105	-	-	4.3 × 10 <sup>5</sup>		A/W
254nm	- 1	5.2 × 10 <sup>5</sup>		-	5.6 × 10⁵	-	A/W
400nm	- 1	7.4 × 105	-	-	7.4 × 105		A/W
633nm	-	4.1 × 10⁵	-		4.1 × 10 <sup>5</sup>		A/W
852nm	—	3.5 × 10⁴	-		3.5 × 10⁴	—	A/W
Gain <sup>E</sup>	-	1.0 × 10 <sup>7</sup>	_	-	1.0 × 10 <sup>7</sup>	_	_
Anode Dark Current F							
After 30 minute Storage in the darkness	-	3	50	—	3	50	nA
ENI(Equivalent Noise Input) <sup>H</sup>	—	1.3 × 10 <sup>-16</sup>		_	1.3 × 10 <sup>.16</sup>	-	w
Time Response <sup>E</sup>							
Anode Pulse Rise Time <sup>1</sup>	-	2.2	-	-	2.2		ns
Electron Transit Time J	-	22		-	22	-	ns
Transit Time Spread (TTS) K	—	1.2			1.2	-	ns
Anode Current Stability L Current Hysteresis Voltage Hysteresis	_	0.1	_	_	0.1	_	%
tonago nyononono							.0

#### NOTES

A: Averaged over any interval of 30 seconds maximum.

- B: The light source is a tungsten filament lamp operated at a distribution temperature of 2856K. Supply voltage is 100 volts between the cathode and all other electrodes connected together as anode.
- C: Red/White ratio is the quotient of the cathode current measured using a red filter(Toshiba R-68) interposed between the light source and the tube by the cathode current measured with the filter removed under the same conditions as Note B.
- D: The value is cathode output current when a blue filter(Corning CS-5-58 polished to 1/2 stock thickness) is interposed between the light source and the tube under the same condition as Note B.
- E: Measured with the same light source as Note B and with the voltage distribution ratio shown in Table 1 below.

#### Table 1:Voltage Distribution Ratio

Electrode	к	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	F	5
Distribution Ratio			1	1	1	1	1	1	1	1	1	

Supply Voltage : 1000Vdc

K: Cathode, Dy: Dynode, P: Anode

- F: Measured with the same supply voltage and voltage distribution ratio as Note E after removal of light.
- G:Measured at a supply voltage adjusted to provide an anode sensitivity of 100 A/m.
- H: ENI is an indication of the photon-limited signal-to-noise ratio. It refers to the amount of light in watts to produce a signal-to-noise ratio of unity in the output of a photomultiplier tube.

$$\mathsf{ENI} = \frac{\sqrt{2q} \cdot \mathsf{Idb} \cdot \mathbf{G} \cdot \Delta \mathbf{f}}{\mathsf{S}}$$

where  $q = Electronic charge (1.60 \times 10^{-19} coulomb).$ 

- Idb = Anode dark current(after 30 minute storage) in amperes. G = Gain.
- $\Delta f = Bandwidth of the system in hertz. 1 hertz is used.$
- S = Anode radiant sensitivity in amperes per watt at the wave-
- length of peak response.
- I: The rise time is the time for the output pulse to rise from 10% to 90% of the peak amplitude when the entire photocathode is illuminated by a delta function light pulse.

## HAMAMATSU

- J: The electron transit time is the interval between the arrival of delta function light pulse at the entrance window of the tube and the time when the anode output reaches the peak amplitude. In measurement, the whole photocathode is illuminated.
- K: Also called transit time jitter. This is the fluctuation in electron transit time between individual pulses in the signal photoelectron mode, and may be defined as the FWHM of the frequency distribution of electron transit times.
- L: Hysteresis is temporary instability in anode current after light and voltage are applied.



Figure 2: Anode Luminous Sensitivity and Gain Characteristics



Figure 4: Typical Temperature Coefficient of Anode Sensitivity



Hysteresis =

 $\frac{l_{max.} - l_{min.}}{l_i} \times 100(\%)$ 

#### (1)Current Hysteresis

The tube is operated at 750 volts with an anode current of 1 micro-ampere for 5 minutes. The light is then removed from the tube for a minute. The tube is then re-illuminated by the previous light level for a minute to measure the variation.

#### (2)Voltage Hysteresis

The tube is operated at 300 volts with an anode current of 0.1 micro-ampere for 5 minutes. The light is then removed from the tube and the supply voltage is quickly increased to 800 volts. After a minute, the supply voltage is then reduced to the previous value and the tube is re-illuminated for a minute to measure the variation.

#### Figure 3: Typical Time Response



Figure 5: Typical Temperature Characteristic of Dark Current (at 1000V, after 30minute storage)



## PHOTOMULTIPLIER TUBES R928, R955

Figure 6: Dimensional Outline and Basing Diagram (Unit : mm)





Figure 7: Optional Accessories (Unit : mm)



TACCA0064EA

% Hamamatsu also provides C4900 series compact high voltage power sup-

plies and C6270 series DP type socket assemblies which incorporate a

DC to DC converter type high voltage power supply.

D Type Socket Assembly E717-21



TACCA0002ED

#### Warning-Personal Safety Hazards

Electrical Shock-Operating voltages applied to this device present a shock hazard.

## HAMAMATSU PHOTONICS K.K., Electoron Tube Center

HAMAMAISU PHOTONICS K.K., Electoron Tube Center 314-5, Shimokanzo, Toyooka-village, Iwata-gun, Shizuoka-ken, 438-0193, Japan, Telephone: (81)539/62-5248, Fax: (81)539/62-220 U.S.A. Hanamatsu Corporation: 360 Foothill Road, Bridgewater, N.J. 08807-0910, U.S.A., Telephone: (1)908-231-0960, Fax: (1)908-231-1218 Germany Hamamatsu Photonics Deutschland GmbH. Arzbergersti: 10, D-82211 Herrsching am Ammersse, Germany, Telephone: (4)98152-375-0, Fax: (49)8152-2558 France Hamamatsu Photonics Tokutschland GmbH. Arzbergersti: 10, D-82211 Herrsching am Ammersse, Germany, Telephone: (4)98152-375-0, Fax: (49)8152-2558 France Hamamatsu Photonics Deutschland GmbH. Arzbergersti: 10, D-82211 Herrsching am Ammersse, Germany, Telephone: (4)98152-375-0, Fax: (3)169 53 71 10 United Kingdom: Hamamatsu Photonics UK Limited. Lough Point, 2 Gladbeck Way, Windmit Hill, Enfleid, Modiesae EN2 7JA, United Kingdom: Telephone: (44)181-367-3560, Fax: (44)181-367-6384 North Europe: Hamamatsu Photonics Norten AB: Fafogatan 7, S1-64-40 Kitsa Sweden, Telephone: (46)7-03-295-0, Fax: (43)169-53-636 Hay: Hamamatsu Photonics Talia: S.R.L: Via Delia Moia, 1/E, 20020 Arese, (Miano), Italy, Telephone: (39)2-935 81 733, Fax: (39)2-935 81 741

TPMS1001E06 MAY 1997



Quite often it becomes necessary to select two or three gratings to achieve efficient light throughput over a broad spectral region That's why SpectraPro monochromators and spectrographs are equipped with multiple-grating turrets as a standard feature. Turrets make grating changes an easy push-button or computer-controlled operation, while reducing the risk of handling the delicate gratings.

Contact your local Roper Scientific sales representative for assistance in selecting the best gratings for your applications

S



SpectraPro Gratings Rev AD

## **GLAN-TAYLOR ULTRA-VIOLET PRISM POLARIZERS**

3

A polarizing prism in which the entrance and exit faces are perpendicular to the incident beam and in which the cement film is replaced by an air spaced interface is known as the Glan prism polarizer. The Glan prism polarizer has a length to aperture ratio of 85 to 1.0 and a useable angular polarized field of about 8% degrees, which is symmetrical with respect to the prism axis at  $\lambda$ = 360nm (center of the ultraviolet spectrum)

It is fabricated in two main types, the Glan-Taylor and the Glan-Foucault, both types transmitting to the limit of the calcite  $\lambda$  = 214nm to  $\lambda$  = 2300nm

The chief advantage of the Glan-Taylor prism polarizer is its increased transmission throughout its spectral range, due to minimized reflection losses which occur because of the unique orientation of the optic axis direction and consequent inci-

SPECIFICATIONS

The following specifications apply to Glan-Taylor and Glan-Foucault types of Glan prism polarizers Length to aperture ratio L/A = 0.85

Spectral transmission range  $\lambda = 214$  nm to  $\lambda = 2300$  nm Larger or smaller sizes to special order Unmounted prisms available by special order

dence of the transmitted beam at approximately the polarizing angle (Brewster angle) at the air spaced interface Approximately 8% greater transmission is attained at  $\lambda = 400$ nm and 10% at  $\lambda =$ 220nm In some applications it is an advantage to employ one polarizer of each type (i.e. in crossed orientation at the entrance and exit slits of a monochromator since the extent of the polarized field is very large in the direction at right angles to the 8½ degree field direction (direction of the optic axis being the plane of polarization)

Special types of Glan prism polarizers having the polarized field symmetrical at  $\lambda = 500$  nm (GLAN-VIS), or the plane of polarization at 45 degrees to the prism sides (GLAN-45), are available on special order Transmission range of Glan-Vis is from  $\lambda = 310$  nm to  $\lambda = 2300$  nm



	CATALOG NO.	DIAMETER (mm) CLEAR APERTURE	MATE- RIAL QUAL- ITY	BEAM DEVIA- TION	EXTINC- TION RATIO @ % OR LESS OF FULL APER- TURE	MOUNTING TUBE DIMENSIONS (INCHES) O.D. × LENGTH	ANG POLA FIE	JLAR RIZED ILD		
	MGTYB8 MGTYB10	8 10	B B	0°5′ 0°5′	1 × 10 <sup>-4</sup> 1 × 10 <sup>-4</sup>	750 × ½ 750 × ½	TOTAL ANG (ASYMMI	NGULAR FIELD		
	MGTYB12 MGTYB15 MGTYB20	12 15 20	B B B	0°5′ 0°5' 0°5′	1 × 10 <sup>-4</sup> 1 × 10 <sup>-4</sup> 1 × 10 <sup>-4</sup>	875 × ¾ 1 125 × ⅔ 1 375 × 1⅓	λ (nm) 214 209	ANGLE 12 7°		
	MGTYA8 MGTYA10 MGTYA12 MGTYA15 MGTYA20	8 10 12 15 20	A A A A A	0°3' 0°3' 0°3' 0°3' 0°3'	$5 \times 10^{-5}$ $5 \times 10^{-5}$ $5 \times 10^{-5}$ $5 \times 10^{-5}$ $5 \times 10^{-5}$ $5 \times 10^{-5}$	750 × ½ 750 × ½ 875 × ¾ 1 125 × ¾ 1 375 × 1%	361 404 589 1041	8 8° 8 5° 8 0° 7 5°		
	MGTYS8 MGTYS10	8 10	St S	0°3′ 0°3′	1 × 10 <sup>-5</sup> 1 × 10 <sup>-5</sup>	750 × ½ 750 × ½	MAXIMUM V	ANGLE OF		
Ł	MGTYS12 MGTYS15 MGTYS20	12 15 20	S S S	0°3′ 0°3′	1 × 10 <sup>-5</sup> 1 × 10 <sup>-5</sup> 1 × 10 <sup>-5</sup>	875 × ¾ 1 125 × ¾ 1 375 × 1½	λ (nm) 214	ANGLE		
	MGTYE8 MGTYE10 MGTYE12 MGTYE15	8 10 12 15	S S S S	0°1′ 0°1′ 0°1′ 0°1	5 × 10 <sup>-6</sup> 5 × 10 <sup>-6</sup> 5 × 10 <sup>-6</sup> 5 × 10 <sup>-6</sup>	750 × 1/2 750 × 1/2 875 × 3/4 1 125 × 7/8	298 361 404 589 1041	38 43 38 27 20		

† Schlieren-Free



1-48

Contact up for further information on any of the products in this catalog
PEMgo

## PERFORMANCE CHARACTERISTICS

## **SPECIFICATIONS**

All parameters are measured at 25 degrees Celsius, driving an I/FS50 modulator head set at 500 waves and 632 8 nM, unless otherwise specified

CHARACTERISTIC	SPECIFICATION	REMARK
FREQUENCY		
Operating Frequency	20 kHz to 100 kHz	Fixed Frequency, Fundamental (f)
Display Range		
f	20 kHz to 100 kHz	
2f .	40 kHz to 200 kHz	
Display Resolution		
f -	1 Hz	
2f	2 Hz	
Display Accuracy		
f	±3 Hz	
2f	±6 Hz	
Reference Stability		
f	±08μS	Referenced to zero crossing
Phase Stability Duty-Cycle		
f	50% ± nominal	Factory adjustable
2f	50% ± nominal	User adjustable from 10 to 90%
RETARDATION AMPLITUDE		
Electronics Stability	0 05 %	After 30 minutes stabilization
Settability	05%, ±25 nm	
Resolution	1/4096 of full scale	
Mınımum Level	Varies	That level required to maintain the head os- cillator in oscillation
WAVENUMBER		
Display	1 to 999,999	
Accuracy	± 1 wn, ± 1 lsb	
Resolution	1 wavenumber	

## CONTROLLER CHARACTERISTIC ELECTRONIC



SPECIFICATION

REMARK

Figure 5.1 Maximum Retardation (wave) vs Wavelength (nm) Model I/FS50 .

MAXIMUM RETARDATION - WAVES

10

.75

50.

25

0







1-7227

## **BIBLIOGRAPHY**

- <sup>1</sup> M. H. Kryder, "Magneto-Optical Storage Materials", Annun. Rev. Matter. Sci. Vol. 23, 411,1993.
- <sup>2</sup> J. M. Daughton, "Magnetic Tunneling applied to Memory", J. Appl. Phys., Vol. 81, No.
  8, 3758, 1997.
- <sup>3</sup> V. Novosad, Y. Otani, A. Ohsawa, S. G. Kim, K. Fukamichi, J. Koike, K. Maruyama,
- O. Kitakami,, Y. Shimida, "Novel Magnetostrictive Memory Device", J. Appl. Phys.,
- Vol. 87, No. 9, 6400, 2000.
- <sup>4</sup> M. R. J. Gibbs, R. Watts, W. Karl, A. L. Powell, R. B. Yates, "Microstructures containing Piezomagnetic Elements", Sensors and Actuators A, Vol. 59, 229, 1997.
- <sup>5</sup> I. J. Garshelis, Force Transducers based on the Stress Dependence of Coercive Force",
- J. Appl. Phys., Vol. 73(10), 5629, 1993.
- <sup>6</sup> M. J. Sablik, "A model for Asymmetry in Magnetic Property Behavior under Tensile and Compressive Stress in Steel", IEEE Trans. Mag., Vol. 33, No. 5, 3958, 1997.
- <sup>7</sup> K. Hayashi, M. Hayakawa, Y. Ochiai, H. Matsuda, W. Ishikawa, K. Aso, "Stress-
- Induced Anisotropy and Permeability of Magnetostrictive Co-based Amorphous Alloys", J. Appl. Phys., Vol. 55, 3028, 1984.
- <sup>8</sup> A. Mitra, M. Vazquez, K. Mandal, S. K. Ghatak, Influence of Stress and Stress-flash annealing on the Magnetic Properties of Amorphous Fe<sub>77 5</sub>Si<sub>7 5</sub>B<sub>15</sub> Wire", J. Appl. Phys., Vol. 70(8), 4455, 1991.

<sup>9</sup> D. C. Jiles, T. T. Chang, D. R. Hougen, R. Ranjan, "Stress-Induced Changes in the Magnetic Properties of some Nickel-Copper and Nickel-Cobalt Alloys, J. Appl. Phys., Vol. 64(7), 3620, 1988.

<sup>10</sup> P. V. Mitchell, K. R. Mountfield, J. O. Artman, "Stress-Induced Anisotropy in Co-Cr Thin Films", J. Appl. Phys., Vol. 63(8), 2917, 1988.

<sup>11</sup> L. Callegaro, E. Puppin, and D. Petrali, "A cell for in-plane, isotropic external stressing of thin films: Inverse Magnetoelastic Effects", Rev. Sci. Instrum., Vol. 68, No. 4, 796, 1997.

<sup>12</sup> L. Callegaro, E. Puppin, "Isotropic in-plane external stressing of ferromagnetic films",
IEEE Transactions on Magnetics, Vol. 32, No. 5., 1065, 1996.

<sup>13</sup> R. Feynman, Feynman Lectures on Physics, Vol 2., 1989.

<sup>14</sup> M. Ohring, *Material Physics of Thin films*, (Academic Press), 1992.

<sup>15</sup> C. Watts, Thesis, Southwest State Texas University, 2000.

<sup>16</sup> B. D. Cullity, *Introduction to Magnetic Materials*, (Addison-Wesley Publishing Company), 1972.

<sup>17</sup> R. E. Hummel, *Electronic Properties of Materials*, 1993.

<sup>18</sup> R. M. Bozorth, *Ferromagnetism*, (American Telephone and Telegraph Company),1978.

<sup>19</sup> K. Honda and S. Kaya, Sci. Reports Tohoku Univ., Vol. 15, 721, 1926.

<sup>20</sup> S. Kaya, Sci. Reports Tohoku Univ., Vol. 17, 639, 1928.

<sup>21</sup> R, M. Bozorth, Rev. Mod. Phys., Vol. 25, 42, 1993.

<sup>22</sup> H. Kagawa and S. Chikazumi, J. Phys. Soc. Japan, Vol. 48, 1476, 1980.

<sup>23</sup> Michael Kuruzar, Unpublished research, University of Notre Dame, 1987.

<sup>24</sup> D. Cheng, *Field and Wave Electromagnetics*, (Add1son-Wesley Publishing), 1989.
<sup>25</sup> Dielectric and Magnetic Materials, Department of Materials, University of Twente, (unpublished), 1977.

<sup>26</sup> M. P. Silverman, *Waves and Grains*, (Princeton University Press), 1998

<sup>27</sup> E. P. Wigner, Symmetries and Reflections, (Indiana University Press), 1967.

<sup>28</sup> J. A. Woollam, B. Johs, C. M. Herzinger, J. Hilfiker. R. Synowicki, C. L. Bungay,

Overview of Variable Angle Spectroscopic Ellipsometer (VASE), Part1: Basic Theory

and Applications, Optical Metrology, Vol. CR72, Proceedings July 18-19, 1999.

<sup>29</sup> A. Nussbaum, and R. A. Phillips, "Contemporary Optics for Scientists and Engineers" (Prentice Hall), 1976.

<sup>30</sup> S. N. Jasperson, S. E. Schnatterly, "An Improved Method for High reflectivity
Ellipsometry Based on a New Polarization Modulation Technique", Rev. of Sci. Instr.,
Vol. 40, No. 6, June 1969.

<sup>31</sup> R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light*, (North Holland Publishing Company), 1977.

<sup>32</sup> J. Kerr, "On Rotation of the Plane of Polarization by Reflection from the Pole of a Magnet", The London, Edinbugh, and Dublin Philosophical Magazine and Journal of Science, May 1877.

<sup>33</sup> W.B. Zepper, "Magneto-Optical Recording Media based on Co/Pt Multilayers",Dissertation, University of Twente, 1991.

<sup>34</sup> Feil, Hans, "Magneto-Optical Kerr Effect:, Dissertation. University of Twente, 1990.
<sup>35</sup> K. Sato, "Measurement of Magneto-Optical Kerr Effect Using Piezo-Birefringent Modulator", Jap. J. of Appl. Phys., Vol. 20, No. 12, December 1981. <sup>36</sup> H. E. Abewichrena, Optical Characterization Laboratory software, Southwest Texas State University, 1999.

<sup>37</sup> Hinds Instruments, "PEM-90 Series I Modulator," 1998.

<sup>38</sup> Acton Reseach Corporation, "SpectraPro-300i Monochromator", 1997.

<sup>39</sup> Acton Reseach Corporation, "FA-448 Six Postion Filter Wheel:, 1997.

<sup>39</sup> Oriel Corporation, "Xenon Arc Lamp Power Supply 8540", 1980.

<sup>40</sup> Oriel Corporation, "Universal Arc Lamp Housings 6450", 1980.

<sup>41</sup> Oriel Instruments, "Xenon Arc Lamp Bulb 6266", 1999.

<sup>42</sup> Hamamatsu, "Photomultiplier Tube 928", 1999.

<sup>43</sup> Karl Lambrecht Coproration, "Glan-Taylor Ultra-Violet Prism Polarizer MGTYS15"1999.

<sup>44</sup> Thor Labs Incorporated, "Photodiode PDA-50", 1999.