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Enhanced AMR in thin $\text{Ni}_{80}\text{Fe}_{20}$ film using $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayer

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Underlayer**

A Thesis

Presented to

The Faculty of the Department of Chemical and Materials Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Phanit Tameerug

May 2000

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Abstract

Enhanced AMR in Thin $\text{Ni}_{80}\text{Fe}_{20}$ Film Using $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ Underlayer

by Phanit Tameerug

Large enhancement in anisotropic magnetoresistance ($\Delta R/R$ or AMR) in $\text{Ni}_{80}\text{Fe}_{20}$ deposited on a thin $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayer was found. The maximum $\Delta R/R$ was observed using the Cr alloy underlayer with 40 to 45 wt% Cr and corresponding to a thickness of approximately 45 Å underlayer. The enhancement of 50 to 150 % was observed for 60 to 500 Å thick $\text{Ni}_{80}\text{Fe}_{20}$. $\Delta R/R$ of 120 Å thick $\text{Ni}_{80}\text{Fe}_{20}$ film is 3.6%, 3.5 %, 2.5 %, and 1.8 % when deposited with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, $\text{Ni}_{58}\text{Cr}_{42}$, Ta, and without underlayer respectively. The $\Delta R/R$ enhancement is attributed to the decrease in the film resistivity (ρ) and the increase in anisotropic resistivity ($\Delta \rho$) of the thin $\text{Ni}_{80}\text{Fe}_{20}$ film. The enhancement is due to the strong and well ordered (111) texture in the $\text{Ni}_{80}\text{Fe}_{20}$ film deposited on $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayer.

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Chapter 1

Introduction

1.1 Background

A key component in computer disk drives is a magnetic read/write head. A magnetic hard disk drive has multiple disks, and each disk surface has one or more read/write heads. The study of magnetic sensors has been ongoing since the beginning of magnetic recording in the 1950s.^{1,2} A magnetic recording sensor must have the capability of converting disk magnetization changes into a large current or voltage with low noise, high signal density detection with small loss in signals, and be cost effective. A magnetoresistive (MR) sensor is the most prominent device for data reading due to these three requirements. Hunt first suggested MR to the magnetic recording industry in 1971.³ IBM announced the first MR read head in 1985, called the IBM 3480.² The current material of choice for MR heads is Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) because of its magnetic properties.

1.2 Why MR

A MR head senses magnetic field signals through the resistance change of the magnetoresistive element.⁴ MR sensor as the read element in magnetic recording systems is interesting because of a number of reasons. First, unlike the thin film inductive head, a MR sensor is a device where the voltage output of MR is limited only by thermal and electromigration consideration. Consequently, as a flux-sensing device, the MR output signals are independent of the velocity of the medium. This is an

important industrial demand for workstations, personal computers, laptops, and notebook products. Currently, industry requires small (3.5", 2.5", 1.8", and 1") high volumetric density disk drives. MR head signal is equally large in both high velocity disk drives (as in workstations) or low velocity disk drives (as in laptops). The comparison of voltage output of an inductive thin film head and MR head as a function of velocity is shown in Figure 1.¹

Figure 1. Comparison of inductive and MR sensor signals as a function of disk velocity.¹

Furthermore, MR head has a greater signal to noise ratio (SNR) than a thin film inductive head. Therefore, MR head can fly higher from the disk for the same signal voltage compared to an inductive head. This helps to increase drive reliability. Finally, MR sensor's function is to read out signals only. For writing, an inductive thin film head is placed on the top of the MR element. The separation of the functions of the read and write elements provides a wide write and narrow read operation. Narrow read means less

opportunity to pick up adjacent noise. This narrow read function leads to an increase in track densities.^{1,2,4}

1.3 Fundamental Properties of Magnetoresistance

1.3.1 Magnetic Properties

Magnetic properties can be directly read from easy and hard axis hysteresis plots (B/H loop). The important parameters are remanent magnetization (B_r), saturation magnetization (B_s), and anisotropic field (H_k). Figure 2 is a typical hysteresis loop for permalloy.

Figure 2. Hysteresis loop.

Magnetic field (H) is in Oersted (Oe) in cgs units and ampere-metre⁻¹ ($A\ m^{-1}$) in SI units. Flux density (B) has units of gauss (G) for cgs units and tesla ($1\ tesla = Wb/m^2$) in SI units. The relationship between flux density (B), magnetization (M), and magnetization field is $B = H + 4\pi M$ in cgs and $B = H + \mu_0 M$ in SI units. Remanence magnetization (M_r) is the

magnetization when the applied field is zero. Saturation magnetization (M_s) is the maximum value of magnetization reached. Coercive force (H_c) is the field required to reduce the magnetization to zero. Anisotropic field (H_k) is the minimum field used to saturate the magnetization in the hard axis direction.

Figure 3. Resistance change of magnetoresistive layer (MRL) as a function of transverse magnetic field and current direction.⁵

1.3.2 Magnetoresistivity Ratio

The magnetization (M) lines up parallel to the easy axis in the absence of an external field. A perpendicular magnetic field (H_y) applied in the y -direction causes M to rotate relative to the field H_y . Figure 3 shows the relationship between the resistance change (R), magnetization (M), and the sense current (I). The resistance of the magnetoresistive layer (MRL) is highest when the sense current (I) is parallel to the magnetization (M) direction (as at point a), and the resistance is the lowest when the sense current (I) and the magnetization (M) direction are perpendicular to each other (as

at point e). Figure 3 shows that the resistance change is a function of the angle (θ) between magnetization and bias current. This is mathematically described as:

$$\rho = \rho_0 + \Delta\rho \cos^2\theta \quad (1)$$

Where ρ_0 is the bulk resistivity. When the magnetization (M) is parallel to the sense current (I), that is θ equals zero, the resistivity reaches its maximum value of $\rho_0 + \Delta\rho$.

When θ equal 90° , the resistivity is a minimum, ρ_0 . The expression in Equation 1 above can be related to anisotropic conductivity for both easy and hard axis. σ_x is the conductivity in the hard axis direction, and σ_y is the conductivity in the easy axis direction.⁶ The conductivity is defined as $1/\sigma_x = \rho_0 + \Delta\rho$ and $1/\sigma_y = \rho_0$.

In order to measure the resistivity of a film; a four-point probe is used. The resistance at (x,y) coordination is called $R(x,y)$, and it is mathematically described as

$$R(x,y) = (\sigma t 2\pi)^{-1} \ln\{[(x+1)^2 + (\sigma_x/\sigma_y)y^2]/[(x-1)^2 + (\sigma_x/\sigma_y)y^2]\} \quad (2)$$

where ϵ is the strain and $\sigma = (\sigma_x + \sigma_y)^{1/2}$ is the conductivity.

The resistivity of any film can be calculated from its sheet resistance (R_s) which is measured by four-point probe. The resistivity is defined in Equation 3.

$$\rho = R_s * t \quad (3)$$

Sheet resistance (R_s) and electrical resistance ($R_{\text{electrical}}$) are also related. Sheet resistance is 4.53 times and 3.90 times higher than the electrical resistance for in-line and square probes respectively. The MR sensitivity ($\Delta R/R_0$) for any kind of probe geometry is:

$$\Delta R/R = \Delta\rho/\rho * M_r \quad (4)$$

M_r is known as the probe factor and depends on the geometry of the probe.

For MR head, the read back voltage must be as high as possible. The MR read back voltage is shown in Equation 5.

$$\Delta V = \Delta R \cdot I \quad (5)$$

In order to reach the maximum read back voltage, one of the following criteria must be met. The criteria are large ΔR , large I , or both ΔR and I , as clearly shown in Equation 5. ΔR can not be calculated directly, and it is the product of anisotropic magnetoresistance ($\Delta R/R$) and the film resistance. Thus, ΔV can also be mathematically described as:

$$\Delta V = (\Delta R/R) R \cdot I \quad (6)$$

Typically, $\Delta R/R$ for permalloy is around 2.0 - 3.0%. Because sheet resistance is inversely proportional to the thickness, thinning the film can increase its resistance, as shown in Equation 3. However, the magnetoresistive layer (MRL) cannot be made as thin as we want due to the surface roughness of the MRL and the substrate. Rough surfaces will increase the surface scattering of electrons and then cause a decrease in the MR response. Meanwhile increasing the sense current will increase the operating temperature of the head and may cause electromigration in the MR element.² Therefore, the best way to increase the read back voltage (ΔV) is to increase the anisotropic magnetoresistance ratio (AMR, or $\Delta R/R$) as seen clearly in Equation 6.

1.4 MR Head Structure

Figure 4. MR read head and thin film inductive write head.¹, pg. 130

The complete MR head is composed of a thin film inductive write head on the top of the MR read head. The read element (MR sensor) is the combination of thin MR film (e.g. $\text{Ni}_{80}\text{Fe}_{20}$), transverse and longitudinal biasing arrangements, and a conductor to carry the current.¹ The complete MR head is shown in Figure 4.

Figure 5. Tri-layer MR element.

Tri-layer MR elements are suitable for MR heads since they have a simple and compact structure. Tri-layers are a MR layer (MRL), a magnetic separation layer (MSL), and a soft adjacent layer (SAL). MR tri-layer is illustrated in Figure 5.⁷ For MR read sensor, the sensitivity is measured by the percent change in resistance. A resistance change is caused by the intrinsic properties of MRL. One preferred technique for depositing these three layers is bias magnetron sputtering.

1.4.1 Magnetoresistive Layer (MRL)

Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) is often used as an MRL material,^{7,8} because the composition provides nearly zero magnetostriction. The magnetostriction of the thin film⁹ is the parameter that characterizes how the magnetoresistive strain changes under the influence of magnetic fields, which effects the bending of the film relative to the substrate. It relates the stress and strain in magnetic material to an anisotropy created by that stress and strain. The Magnetostriction constant (λ) is unitless. It is calculated from

$$\lambda = d \cdot t_s^2 / (3 \cdot t_f \cdot l^2 \cdot \epsilon), \quad (7)$$

where t_f and t_s are the thickness of the film and the substrate respectively, d is the film deflection, l is the distance from the clamping edge, and

$$\epsilon = E_f(1-\nu_s) / E_s(1+\nu_f), \quad (8)$$

where E_f and E_s , ν_f , ν_s are Young's modulus and Poisson' ratio of the film and substrate respectively. High magnetostriction in a material means high residual stress in the film

and can induce anisotropic magnetoresistivity ratio (AMR) of the film. Thus, magnetostriction (λ) is one of the important parameters used to prevent AMR characteristic degradation. For the right film composition, λ can be made small. Polycrystalline permalloy film at composition $\text{Ni}_{80}\text{Fe}_{20}$ has a nearly zero magnetostriction coefficient.¹⁰

Since the function of the MR layer is to sense signals from the disk medium, the layer is also called the sensing layer. The sensing layer responds to external magnetic fields. In the absence of external magnetic fields, the sensing layer will spontaneously magnetize itself parallel to the longitudinal direction (parallel to the medium radius), the so-called easy axis that is shown in Figure 6.¹

Figure 6. MR head basics.¹

The MRL's magnetic orientation (M) refers to the magnetization of the MRL. It is rotated from parallel (easy axis or longitudinal direction or x direction) to the perpendicular position (hard axis or transverse direction or y direction), as the

perpendicular magnetic field (H_y) is increasingly applied. The hard axis direction has the highest energy for magnetization (y-axis or transverse axis). In Figure 6, the perpendicular magnetic field (H_y) is composed of an external magnetic field (H_{disk}) from the rotating medium and the fixed magnetic field ($H_{\text{transverse bias}}$) from the soft adjacent layer. The reading process is shown in Figure 7.

Figure 7. The magnetic reading process.⁵

The relationship of the external fields and the transverse bias fields is shown below:

$$H_y = H_{\text{disk}} + H_{\text{transverse bias}} \quad (9)$$

1.4.2 Soft Adjacent Layer (SAL)

The Soft Adjacent Layer (SAL) is located at the bottom of the MR-tri layer, that is, under the magnetic spacer layer as shown in Figure 5. CoZrMo is often used for this

layer.^{1,7,8} The function of the SAL is to give sufficient bias to the magnetic layer to improve linearity and sensitivity in the response. When DC current passes through the MR layer, the current (I) generates magnetic fields surrounding it. Part of the flux reaches the SAL, which is magnetically soft and is magnetized easily by the field. The magnetization of the SAL now provides an external field to the MRL in the transverse direction and assists the rotation of the magnetization in the MRL. SAL materials have a low anisotropy field (H_k), low magnetoresistance ratio ($\Delta R/R_0$ or $\Delta\rho/\rho_0$) and high resistivity (ρ). A good SAL must provide low magnetostriction to prevent magnetic property degradation during head manufacturing.

1.4.3 Magnetic Separation layer (MSL)

The Magnetic Separation Layer (MSL, spacer layer, or underlayer) is a layer underneath the sensing layer and on the top of Soft Adjacent Layer. Titanium and tantalum are often used for this layer. The function of a spacer layer is to separate the two magnetic layers (MRL and SAL). This layer leads the SAL to achieve an excellent bias. A good spacer needs to have high resistivity, be nonmagnetic and electrically insulating, and have small $\Delta R/R$ (or $\Delta\rho/\rho$). The highest maximum resistivity change ($\Delta\rho_m$) value is achieved when the MSL thickness is zero, because the net current through the MRL is increased. However, the MR layer is not magnetically biased without the presence of the spacer layer. This is because when the MRL and the SAL contact each other, the signal response will be canceled. On the other hand, a thick spacer will give

low output voltage which is due to electrical shunting.⁷ Also a thin MSL can improve the epitaxial growth of the MRL, improving its microstructure. Tantalum is currently used as a Magnetic Spacer Layer (MSL) for AMR application. The major problems with tantalum are the thermostability and electromigration at high temperature. At high temperature Ta tends to diffuse into the permalloy film resulting in device degradation. Since thermal considerations in high-density hard drives are very important, the spacer must fulfill this need for low interdiffusion.

1.5 Thesis objective

This thesis' objective was to identify a magnetic spacer layer material that can be used to enhance the $\Delta R/R$ of permalloy films for AMR head applications. The initial information on materials selection came from private discussions with Wen Yuang Lee (IBM-ARC). The potential materials included pure elements, binary alloys, and ternary alloys. The first objective was to determine the magnetic spacer that can enhance $\Delta R/R$ of permalloy significantly. The second objective was to study the mechanism of enhancement for the particular spacer. Using a four-point probe, BH loop tracer, Proton Induced X-Ray Emission (PIXE), and Grazing Incident X-Ray Diffraction (GIXD) useful material was selected for the MSL (spacer layer or underlayer) and an initial investigation into the mechanism was completed.

Chapter 2

Literature Review

The literature was reviewed in two areas. The first area focused on the articles describing the relationship between microstructure and magnetic properties of anisotropic magnetoresistive (MR) heads. The articles in this area provided a basic understanding of the possibility that anisotropic magnetoresistive sensitivity (AMR or $\Delta R/R$) in permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) can be enhanced. The second area of interest was the research done to enhance those properties.

The performance of a MR head is due to the interaction of three layers of the magnetoresistive element. These three layers are the magnetoresistive layer (MRL), the magnetic separation layer (MSL), and the soft adjacent layer (SAL). The magnetic properties are related to the tri-layer microstructure and the sputtering parameters. The magnetic properties are H_c , H_k , $\Delta R/R$ ($\Delta\rho/\rho$), and magnetic thickness. The microstructures include grain size, grain boundary formation, $\langle 111 \rangle$ texture, and interfacial contact. Finally, the sputtering parameters are chamber vacuum pressure, composition, film thickness, deposition rate, sputter power, deposition temperature, and argon pressure.

Many materials have been studied to find a way to promote the AMR sensitivity and magnetic properties of an MR head, such as NiFeTa ,¹¹ permalloy/W,¹² permalloy/Zr,¹³ permalloy/Ti,¹⁴ permalloy/Nb,¹⁵ permalloy/(Mo, Ta, Al, Cu, Cr, and

Au,¹⁶ NiFeMo,¹⁷ NiFeCr,¹⁸ NiFeX (X = Au, Pt, Ag, Cu, Pd, Co, Ru and ZrO₂),¹⁹⁻²¹ and FeNiCo/Cu,²² Each material was used differently to enhance the AMR sensitivity. For example, some of them were used as the SAL, and some of them were used as the MR layer.

A general discussion of microstructure effects on magnetic properties of AMR trilayers will be in Section 2.1. Section 2.2 reviews all materials that have been studied for AMR sensitivity enhancement. Finally, section 2.3 is a summary of the results.

2.1 The Effect of Microstructure on MR Layer

2.1.1 Spacer and Permalloy Criteria

A good magnetic spacer must have high resistivity (electrical insulator), be non-magnetic, and have near zero $\Delta R/R$. After depositing permalloy on the top, the spacer must enhance $\Delta R/R$ of permalloy film. The interface between the spacer and the permalloy film plays an important role in determining the microstructure of the permalloy layer. The growth texture of permalloy is in the $\langle 111 \rangle$ direction. Figure 8 shows the growth texture of a pure permalloy film.

Figure 8. A schematic cross-section of the atomic arrangement of permalloy ($\text{Ni}_{80}\text{Fe}_{20}$).²³

For the interface between spacer and permalloy to have a small misfit, the interplanar spacing of the spacer must be about the same as permalloy or close to permalloy. Table I shows the typical growth textures of selected structures.

Table I. Growth texture and crystal structure.

Structure	Thin Film Texture
BCC	{110}
FCC	{111}
HCP	{0001}

The growth of permalloy film will be epitaxial on the spacer. The grains in the permalloy layer are expected to grow in columnar fashion for the film to satisfy the high magnetic properties.²³ Therefore, $\Delta R/R$ is maximum, and resistivity, coercive force, and anisotropic fields are minimum.

Tantalum is the current spacer material in the magnetic recording industry. Tantalum can enhance $\Delta R/R$ of permalloy up to 2.2%. It is believed that tantalum helps a permalloy to grow with the strong texture in $\langle 111 \rangle$ direction. Using substrate bias during tantalum deposition will reduce the density of crystalline defects in a growing tantalum film. For the permalloy film with the substrate bias, the permalloy film achieves better crystallinity along with an enhancement in columnar growth in $\langle 111 \rangle$ direction.

2.1.2 Film Boundary

In thin permalloy deposition, e.g. by evaporation or sputtering, the grains are generally not isotropic in form but tend to grow in a columnar fashion. The columnar axis is normal to the film plan. Large grain boundaries influence a large scattering rate of conduction electrons at the boundaries. The resistivity of the thin film is calculated from three kinds of electron scattering:²⁴

- A. An isotropic background scattering (due to the combined effects of phonon and point defect).
- B. A scattering due to the distribution of the grain boundaries.

C. A scattering due to the roughness of the external surface.

2.1.3 Grain Boundary Scattering Model and Electron Mean Free Path

Rijks *et al.*²⁵ have demonstrated copper and permalloy grown on a tantalum layer. Grain boundaries are an important source of electron scattering as a small grain size is found after growth in the copper and permalloy on top of the tantalum (average grain diameter is considerably smaller than the film thickness). In the permalloy the small grain size leads to a reduction of the effective spin dependence of the scattering. In order to treat the AMR effect, the mean free path of the electron is considerably dependent on the angle between its velocity and the magnetization. The model assumes that the diffusive electron scattering is at the film boundaries. The grain boundary scattering is taken into account in the mean free path of the electron (λ). The mean free paths are the only adjustable parameter. They are given by:

$$1/\lambda = 1/\lambda_i + 1/\lambda_{gr} \quad (10)$$

Respectively, λ_i and λ_{gr} are the mean free paths for intrinsic scattering and grain boundary scattering. Typically, mean free paths are spin dependent. Equation 10 is used when the intrinsic mean free path is larger than the grain size (D). The average grain size is usually estimated by Transmission Electron Microscopy (TEM). The low value of λ_{gr} (t/D) indicates a high electron scattering probability at the grain boundary. Therefore, for a permalloy film grown on a tantalum layer it is found that grain boundaries are an important source of electron scattering. The film (permalloy) is spin dependent.

Therefore, the increase in grain boundary scattering leads to the reduction of the effective spin dependence of the scattering. Grain boundary scattering will reduce the magnetoresistance (MR) of the permalloy.

2.1.4 Epitaxial Growth of Permalloy on Ta

A tantalum layer is used to improve the (111) texture of the permalloy film.²²⁻²⁴ The permalloy has columnar growth perpendicular to the tantalum layer. Rijks *et al.*²⁶ have shown that a permalloy film grown on a Si (100)/Ta texture exhibits columnar grain structure. Whereas, with a permalloy film grown on SiO_x, the film did not exhibit columnar texture. The TEM study on the influence of a tantalum layer on a microstructure of permalloy film has shown that the tantalum layer resulted in increasing the permalloy grain size. There is an assumption that two types of random space planes can represent grain boundaries, which are perpendicular and parallel to the tantalum film with an average separation of d .²²

2.1.5 Permalloy Thickness vs. Its Grain Size and Resistivity

The Fuchs-Sondheimer theory^{24,26-28} is a well-known way to explain the origin of resistivity in thin films. Fuchs theory²⁸ is shown by Equation 11.

$$\rho \lambda = 12\pi^3 \hbar / (e^2 A) \quad (11)$$

where ρ , λ , and A are resistivity, the average mean free path, and the total area of Fermi-surface, respectively. Figure 9 shows the relationship between the resistivity (ρ) and the permalloy thickness.

Figure 9. Resistivity versus film thickness for various permalloy thickness.²⁸

The resistivity in thin polycrystalline film is always higher than the original bulk material, and increases rapidly due to the material's thickness increasing.²⁸ This is because of the scattering mechanisms of the bulk material combined with the boundary condition for its external surfaces. In thin film, grown in a vacuum by evaporating or sputtering, the decrease in intrinsic resistivity (or the intrinsic electron mean free path) and the increase in thickness is due to the increase in grain size. The distance between grain boundaries is generally smaller than the electron scattering mean free path. Therefore, the grain boundary contribution is taken into account with the resistivity.²⁹

2.2 The Enhancement Materials for AMR

2.2.1 NiFeTa Thin Film as a Soft Adjacent Layer (SAL)

Kitada and Yamamoto¹¹ discussed the effect of tantalum addition on the magnetic properties of permalloy films. The alloy compositions studied were $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Ta}_x$ with x being 0 to 0.105 wt%. The film was sputtered onto a glass substrate between room temperature and 300 °C. Saturation magnetization (B_s), magnetoresistance ratio ($\Delta R/R$), and an anisotropic field (H_k) decrease with an increase in tantalum content. The coercivity remains constant at 125 Am^{-1} when zero to 10%Ta is added to $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Ta}_x$. For instance, the saturation magnetization decreases from 1.0 to 0.25 Tesla when Ta content increases from zero to 10 %. The electrical resistivity increases linearly with increasing in Ta content as shown in Figure 10.

Figure 10. Composition dependence of (●) magnetoresistive sensitivity and resistivity (○) of $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Ta}_x$ film.¹¹

$(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Ta}_x$ (with 5-6 wt.% Ta) has the potential for use as the SAL in AMR elements since this film has good soft magnetic properties, has high electrical resistivity, has low magnetoresistivity, and has high saturation magnetization.

2.2.2 Permalloy/(W, Zr, Ti, or Nb)

Kitada *et al.*¹²⁻¹⁵ studied their film applications to magnetoresistive elements. The properties and the start temperature of interdiffusion of the permalloy/W, Zr, Ti, Nb interfaces and reactions were used for understanding thin film diffusion and new layer growth mechanisms.

In a permalloy/W¹² thin film system, W, Ni, and Fe mutually diffuse. This causes a reduction in magnetic and magnetoresistive properties of the permalloy layer. The temperatures where the coercivity and the electrical resistance start to increase are proportional to the melting point and the activation energy of self-diffusion.

In the permalloy/(Zr, Ti),^{13,14} Kitada *et al.* found that Ni atoms prefer to diffuse away from the permalloy layer into Zr and Ti layers. This diffusion results in the growth of an amorphous phase between Zr or Ti and the permalloy. Consequently, the magnetic properties of the permalloy decrease. The interdiffusion temperature of Zr/permalloy is 75°C higher than Ti/permalloy.

The magnetic properties of permalloy/Nb are same as the magnetic properties of W, Zr, Ti/permalloy. An intermetallic compound Nb_2NiFe_3 is formed by annealing at

500 °C, and the magnetic and electrical properties of the permalloy change. This compound formation and its interdiffusion give the permalloy film a very high coercivity.

2.2.3 Permalloy/(Mo, Ta, Al, Cu, Cr, or Au)

Kitada and Yamamoto¹⁶ developed these contact materials for a thin permalloy film. In their study it is shown that the contact metal must not react with the permalloy film, or these reactions will cause device degradation. The reactions of thin permalloy film are studied to determine the behavior between these electrode materials and the permalloy film. Au, Cu, Mo, and Ta are the possible materials for electrodes. Al, Cu, Cr, and Au films react with the permalloy film between 250° C and 300 °C. Ta and Mo do not react up to 400 °C. Therefore, Mo and Ta are good electrode materials for thin permalloy film devices.

2.2.4 NiFeMo Film Properties

Nguyen *et al.*¹⁷ presented the comparative measurements on thin film of Ni₈₀Fe₂₀ and Ni₈₀Fe₁₅Mo₅ deposited by r.f. sputter. The film resistivities were measured under the influence of the deposition parameters, thickness, and sample shape. The saturation magnetization is in the range of 0.6-0.8 Tesla and independent of the deposition parameters (pressure, power, and rate). The H_c decreases as the deposition power increases. This is because the high deposition rate at high deposition power results in

small grain size (causing large resistivity). The resistivity of $\text{Ni}_{80}\text{Fe}_{15}\text{Mo}_5$ is around $60 \mu\Omega\text{cm}$.

2.2.5 NiFeCr Corrosion

Rice *et al.*¹⁸ has shown that the addition of chromium to permalloy exhibits good corrosion resistance. However, these additives degrade the magnetic properties of film. For an application as a magnetic recording head, the head cannot stand corrosion at all. This is because of the very small space between head and media. Figure 10 depicts the resistivity (ρ) and the magnetoresistive coefficient ($\Delta\rho/\rho$) versus chromium concentration. Rice *et al.*¹⁸ proposed a new idea to understand the increase in resistivity after adding the third element to permalloy. It may not be due to the structure sensitivity, but may be due to the change in electronic band structure of the alloy instead.

Figure 11. The resistivity (ρ) and the magnetoresistive coefficient ($\Delta\rho/\rho$) versus chromium concentration.¹⁸

The rapid reduction of $\Delta\rho/\rho$ below 1.0%Cr due to the change in chromium concentration to the permalloy makes chromium addition undesirable for magnetoresistive layer (MRL). The reduction of $\Delta\rho/\rho$ of the NiFeCr film is not due to the increase in ρ but is due to the large reduction in $\Delta\rho$ (intrinsic property).

2.2.6 NiFeX (X = Au, Pt, Ag, Cu, Pd, Co, Ru, ZrO₂)

Komura *et al.*,¹⁹ Xue *et al.*,²⁰ and Chen *et al.*²¹ studied the effect of adding a third element, X, to permalloy alloy films. These studies were on anisotropic magnetoresistive ratio $\Delta\rho/\rho$ and other magnetic properties. The two possibilities to enhance the $\Delta\rho/\rho$ ratio are either by increasing $\Delta\rho$ or reducing ρ , or increasing both at the same time.

Xue *et al.*²⁰ used NiFeX as a soft magnetic underlayer for a CoPt film. The study indicated that the FCC $\langle 111 \rangle$ texture of the NiFeX film assisted the growth of the HCP $\langle 002 \rangle$ texture of the CoPt layer.

Chen *et al.*²¹ also studied NiFeX films as a SAL application for AMR tri-layer sensor. Normally, the addition of the third element into an alloy film reduces the magnetic properties of the film and increases the electrical resistivity of the film. For SAL application NiFeX must exhibit high electrical resistivity to minimize current shunting. Also the NiFeX as a SAL must have soft magnetic properties and low $\Delta\rho/\rho$ ratio. The effect of the third element on the permalloy properties such as magnetization saturation field (B_s), resistivity (R), and $\Delta\rho/\rho$ ratio are shown in Figures 12, 13, and 14.

Figure 12. The normalized B_s of NiFeX film vs. X atomic concentration.²¹

Figure 13. The resistivity of NiFeX film vs. concentration.²¹

Figure 14. Anisotropic magnetoresistance of NiFeX film versus X atomic concentration.²¹

Among the NiFeX films, NiFeNb and NiFeZr were found to be the best candidates for Soft Adjacent Layer application. Other films provide good soft magnetic properties, but low electrical sheet resistance.

2.3 Literature Summary

Table II summarizes different materials and their properties and functions that have been studied. The magnitude of $\Delta\rho/\rho$ ratio of any permalloy, alloy, and ternary alloy (NiFeX) is found to strongly depend on the film thickness and the additional third elements. Adding the third element to permalloy will lower the $\Delta\rho/\rho$ ratio but may gain another advantage, such as corrosion resistance.

The studies of the materials were for application as either MRL application or SAL. For Magnetic Separation Layer (spacer), tantalum is now used in the AMR tri-layer industry. No research has been documented on tantalum spacer or any other spacer material for AMR head applications. The reason for using tantalum is not clearly understood. Presently, one reason found is that tantalum can enhance the (111) texture of permalloy film and assist permalloy to have low grain boundary scattering in the case of GMR. No information on the microstructure related to magnetic properties after using Ta or other material spacer in tri-layer AMR has been provided.

Table II. Materials and Functions Summary.

Material	Purpose	Properties/Result
$(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Ta}_x$ $x = 0-10.5 \text{ wt } \%$ ^{25,26}	SAL	$B_s, H_k, H_c \propto 1/(\text{Ta } \%\text{wt})$
$\text{Ni}_{80}\text{Ni}_{20}/\text{X}$ $\text{X} = \text{W}, \text{Zr}, \text{Ti}$ ¹²⁻¹⁴	The study of interdiffusion between X and $\text{Ni}_{80}\text{Fe}_{20}$ film	$\Delta\rho/\rho$ degrades after annealing
$\text{Ni}_{80}\text{Fe}_{20}/\text{Nb}$ ¹⁵	Shunt layer	Interdiffusion starts at $T=375 \text{ C}$
$\text{Ni}_{80}\text{Fe}_{20}/\text{X}$ $\text{X}=\text{Al}, \text{Cu}, \text{Cr}, \text{Au}$ ¹⁶	Contact material for thin permalloy film	Reaction occurs above $250-300 \text{ C}$
$\text{Ni}_{80}\text{Fe}_{20}/\text{X}$ $\text{X}=\text{Mo}, \text{Ta}$ ¹⁷	Contact material for thin permalloy film	Reaction occurs above 400 C
$\text{Ni}_{80}\text{Fe}_{15}\text{Mo}_5$ ¹⁷	The influence of thickness, sample shape, deposition parameters to the magnetic properties	$B_s = 0.6-0.8\text{T}$ $R = 65 \mu\Omega\text{cm}$
$(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ $x = 0-10 \text{ wt}\%$ ¹⁸	The study of magnetic properties due to corrosion	Good corrosion resistance, low H_c & high B_s , $\Delta\rho/\rho = 2.8 - 0.3\%$
NiFeX , $\text{X} = \text{Au}, \text{Pt}, \text{Ag}, \text{Cu}, \text{Pd}, \text{Co}, \text{Ru}, \text{ZrO}_2$ ¹⁹⁻²¹	SAL, the effect of third elements	Adding X decreases the B_s and $\Delta\rho/\rho$, but increases ρ

Chapter 3

Experimental Procedure

3.1 Experimental Plan

The experimental plan was divided into three phases: (I) material exploration (composition dependence effect), (II) thickness dependence, and (III) structure characterization.

Phase I was material exploration. Magnetic transport measurement was done after every set of film deposition. The goal of this phase was to determine the composition range of the spacer that had the potential to enhance $\Delta R/R$ of permalloy. The full exploration of the possible spacer materials, based on the discussion and the literature review, was carried out in this step. The result of the literature review and the discussion with Dr. Wen Lee (IBM) led to the ideas of material choices. The potential materials include pure element, bilayer alloys, and ternary alloys. A pure element is Ta. The binary alloy is $\text{Ni}_{(1-x)}\text{Cr}_x$, and the ternary alloy is $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$. The transport magnetic measurements were done simultaneously in Phase I to analyze the magnetic properties of a permalloy film under an influence of a spacer. H_k , $H_{c\text{-easy}}$, $H_{c\text{-hard}}$, magnetic thickness, and $\Delta R/R$ were measured by B/H loopers to determine the magnetic properties of the interesting films for Phase II. The ternary alloys of $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and the binary alloy of $\text{Ni}_{(1-x)}\text{Cr}_x$ at 40-45 wt% Cr do show the possibility of $\Delta R/R$ enhancement in permalloy.

Phase II investigated the thickness dependence. The goal of this step was to investigate the effect of the thickness of the particular spacer layer resulting from Phase I on the $\text{Ni}_{80}\text{Fe}_{20}$ film. The composition of the spacer was fixed at the composition that gave the highest $\Delta R/R$ to $\text{Ni}_{80}\text{Fe}_{20}$ (resulting from Phase I). Then the thickness was varied from 80 Å to 15 Å. $\text{Ni}_{58}\text{Cr}_{42}$ showed the greatest $\Delta R/R$ enhancement at 50 Å. Again, the magnetic transport measurement was done along with the film deposition. The details of the result will be shown in Chapter 4.

Phase III was the structure characterization. The purpose of this phase was to answer why the enhancement of $\text{Ni}_{80}\text{Fe}_{20}$ occurs after using tantalum or a new spacer layer. After the permalloy/ spacer film was deposited, Grazing Incident X-ray Diffraction (GIXD) was used to analyze the film microstructure such as grain size, growth texture, and interplanar spacing. Photon Induced X-ray Emission (PIXE) was used to analyze the exact film composition.

The deposition technique for the entire thesis was magnetron sputtering deposition, for which details are given in the Appendix . The advantages of the system are high sputtering rate, large area deposition, uniform deposition, and low substrate temperature.

3.2 Experimental Procedure

3.2.1 Sample Preparation

Experiments used 1-inch diameter glass substrates on which films were deposited. Substrates were cleaned by sulfuric acid etch before films were deposited. An IBM

magnetron sputtering system was used for all depositions. Films were deposited on glass substrates with 150 Oe biasing magnetic field. All other sputter parameters such as argon pressure (3 mtorr), sputter power (200W for $\text{Ni}_{80}\text{Fe}_{20}$), substrate temperatures (20°C-30°C) were controlled and monitored directly by the controller. Each pumpdown can deposit eight different compositions. The composition and the thickness were designed as shown in Tables III and IV. The composition of each sample was controlled by the sputter power (rate in Å/sec) of the corresponding targets. Each pumpdown took eight hours to reach the vacuum requirement for the sputtering, which is 1×10^{-7} torr. Thickness calibration (tooling factor) was needed after changing any new target. Immediately after the deposition, samples were taken to a four-point probe to measure the film sheet resistance, to the profilometer to measure the physical thickness, and to B/H loopers to measure the magnetic properties (H_k , $H_{c\text{-easy}}$, $H_{c\text{-hard}}$, B_s , Magnetic thickness) and $\Delta R/R$ measurement. The instruments and the property measurements are described later in the Appendix.

3.2.2 Phase I: The Effects of the Spacer Composition on the $\Delta R/R$ and the Magnetic Properties of Permalloy

The composition of spacers, which are $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and $\text{Ni}_{(1-x)}\text{Cr}_x$, were controlled by the relative deposition rate of $(\text{Ni}_{80}\text{Fe}_{20})\text{:Cr}$, and $\text{Ni}\text{:Cr}$ respectively. “X” in weight percentage was varied for each alloy. The spacers were fixed at 50 Å in thickness. The composition matrix is shown in Table III.

Table III. The spacer film composition (wt. %) with 150 Å $\text{Ni}_{80}\text{Fe}_{20}$ film deposited on the top.

Position	1	2	3	4	5	6	7	8
$\text{Ni}_{(1-x)}\text{Cr}_x$ →	80	60	50	55	40	45	30	25
First Run →								
Second run →	60	50	48	46	44	42	40	38
Third run →								
($t=50$ Å)	50	49	47	45	44	43	41	39
$(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$	80	60	50	55	40	45	30	25
First Run →								
Second run →	60	50	48	46	44	42	40	38
Third run →								
($t=50$ Å)	50	49	47	45	44	43	41	39

Column 1 is the spacer layer composition. Position 1 to position 8 is the substrate position in the sputtering chamber. The value “x” is in weight %. The thickness of the underlayers in Table III was fixed at 50 Å. Cr is varied from 80% to 25% in the first run with the step around 5-10%, from 60% to 38% with the step of 2-10% in the second run, and from 50% to 39% with 1-3% step in the third run. Vacuum pressure in the sputtering system was 1×10^{-7} torr. Substrate temperature was 20°C to 30°C. Argon pressure was at

5×10^{-2} torr. After depositing the spacer, a 150 Å $\text{Ni}_{80}\text{Fe}_{20}$ film was deposited sequentially. The film schematic is shown in Figure 15.

Figure 15. The schematic of the film from phase I. The spacers are

After films were deposited, the magnetic properties of permalloy/spacer and $\Delta R/R$ of the $\text{Ni}_{80}\text{Fe}_{20}$ were measured by B/H loop. The composition with the maximum $\Delta R/R$ enhancement to permalloy was made again to confirm the repeatability.

The more accurate composition was determined later in Phase III by PIXE (or RBS). The result of magnetic property measurement and $\Delta R/R$ provide the information of choosing films for Phase II. The candidate spacers were $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Ni}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$.

3.2.3 Phase II: The Effect of the Spacer Thickness on $\Delta R/R$ and the Magnetic Properties of Permalloy

The sample with the highest $\Delta R/R$ by the results of the experiment in Phase I were used. Eight different spacer thickness were deposited. The spacer layer thickness is varied as shown in Table IV. The schematic of the films is shown in Figure 16.

$\text{Ni}_{80}\text{Fe}_{20}$ 150 Å
Spacer: 35 < t < 80 Å
Glass Substrate

$\text{Ni}_{80}\text{Fe}_{20}$: 60 < T < 500 Å
50 Å Ta or 45 Å Spacers
Glass Substrate

Figure 16. a) The schematic of run C and D.

b) The schematic of run E and F.

Table IV. The thickness matrix in Angstroms unit

Experiment #	Film Structure	1	2	3	4	5	6	7	8
A	$\text{Ni}_{80}\text{Fe}_{20}$ (Reference films)	500	300	200	180	150	120	110	90
B	$\text{Ni}_{80}\text{Fe}_{20}(\text{TÅ})/\text{Ta}(50\text{Å})$; T=(Å)	500	300	200	180	150	120	110	90
C	$\text{Ni}_{80}\text{Fe}_{20}$ (150Å)/($\text{Ni}_{80}\text{Fe}_{20}$) ₅₆ Cr ₄₄ t=(Å) Run 1	80	60	55	50	45	40	38	35
	Run 2	50	58	53	47	45	43	41	38
D	$\text{Ni}_{80}\text{Fe}_{20}$ (150Å)/ $\text{Ni}_{58}\text{Cr}_{42}$ t=(Å) Run 1	80	60	55	50	45	40	38	35
	Run 2	50	58	53	47	45	43	41	38
E	$\text{Ni}_{80}\text{Fe}_{20}$ (T Å) / $\text{Ni}_{58}\text{Cr}_{42}$ (45Å) ; T=(Å) Run 1	500	300	200	180	150	120	110	90
	Run 2	250	160	140	130	120	100	80	60
F	$\text{Ni}_{80}\text{Fe}_{20}$ (T Å) /($\text{Ni}_{80}\text{Fe}_{20}$) ₅₆ Cr ₄₄ (45 Å) Run 1	500	300	200	180	150	120	110	90
	Run 2	250	160	140	130	120	100	80	60

Column 2 is the film structures. Position one to position eight show the film thickness of each sample made during a single pumpdown. “T” and “t” are the thickness of the $\text{Ni}_{80}\text{Fe}_{20}$ film and the spacer respectively. $\text{Ni}_{80}\text{Fe}_{20}$ in run A, B, E, and F was deposited at different thickness. $\text{Ni}_{80}\text{Fe}_{20}$ in run C and D were fixed at 150 Å with difference underlayer thickness for determining the optimum underlayers’ thickness. Run A was use as a reference for $\Delta R/R$ measurement. Run B was use as a reference for $\Delta R/R$ measurement of $\text{Ni}_{80}\text{Fe}_{20}$ with 50 Å Ta underlayer. After the optimum underlayer thickness were determined, run E and F were deposited to measure the effect of underlayers ($\text{Ni}_{58}\text{Cr}_{42}$, and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$) on difference $\text{Ni}_{80}\text{Fe}_{20}$ thicknesses. $\text{Ni}_{80}\text{Fe}_{20}$ thickness was changed from 60 Å to 500 Å.

3.2.4 Phase III: The Effects of Microstructure on the $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ Film Under the Influence of the Spacer

The objective of Phase III is to understand the enhancement mechanism. The 60 Å to 500 Å $\text{Ni}_{80}\text{Fe}_{20}$, 45 to 300 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, 45 to 300 Å $\text{Ni}_{58}\text{Cr}_{42}$ were deposited. Pure $\text{Ni}_{80}\text{Fe}_{20}$ films were used as the referent data. $\text{Ni}_{58}\text{Cr}_{42}$ and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ are selected because of its highest $\Delta R/R$ enhancement. $\text{Ni}_{20}\text{Cr}_{80}$ is use for the comparison as ineffective spacer. GIXD were used to identify the grain size, growth texture, and interplanar spacing of all the films above. Regaku Rotaflex was used to correct the diffraction pattern data for the entire microstructure study. Electrons, inside x-ray tube, were rapidly drawn from a tungsten filament to a copper target by 50 kV across the tube. Tube current was set at 200 mA. X-rays were emitted from the focus spot passed through

a 1.5x1.5 mm. slit window. The incident beam fell onto the sample with circular shape. Two perspective comparisons were done. First, microstructure was observed for fixed underlayers (at optimum thickness and composition) with different $\text{Ni}_{80}\text{Fe}_{20}$ thickness. Second, microstructure was observed for fixed $\text{Ni}_{80}\text{Fe}_{20}$ thickness on fixed thickness of Ta, $\text{Ni}_{58}\text{Cr}_{42}$ and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer. PIXE was used to identify the film composition of all the individual spacer. The PIXE results showed the film to be within 1% of the nominal composition and no further discussion will be included.

3.3 Data Analysis

In order to interpret the results in Chapter 4, the relationship between $\Delta R/R$ and $\Delta\rho/\rho$, sheet resistance and electrical resistance, resistance and resistivity, $\Delta\rho/\rho$ and ρ , and grain size and full width at half maximum are described below.

3.3.1 $\Delta R/R$ and $\Delta\rho/\rho$

Magnetoresistance ratio measurement ($\Delta R/R$) can be related to the basic material magnetoresistivity ($\Delta\rho/\rho$). Magnetoresistivity can be measured by reading the value of electrical resistance with a saturated magnetic field in easy and hard axis. The magnetoresistance ratio

$$\Delta R/R = R_x - R_y / (0.5 * (R_x + R_y)) \quad (10)$$

can be used to refer to the materials' Magnetoresistivity ratio. Under an approximation of $\Delta\rho/\rho$ is less than one ($\Delta\rho/\rho \ll 1$) and with the use of equation 4, the relationship of $\Delta R/R$ and $\Delta\rho/\rho$ is shown as

$$\Delta R/R = \Delta \rho/\rho * M_r$$

The value of M_r , which is the probe factor, is dependent on the probe geometry.⁶ For the entire thesis, rectangular probe was used for the $\Delta R/R$ measurements. Rectangular geometry gives a factor $M_r = 0.993$, which is close to one. Therefore, the fractional resistance change ($\Delta R/R$) is almost identical with the basic material magnetoresistivity ratio ($\Delta \rho/\rho$). In this thesis, the two will be used interchangeably. Most of the time $\Delta R/R$ is presented in percent (typically in a few percent).

$$\Delta R/R = \Delta \rho/\rho \quad (11)$$

3.3.2 Sheet Resistance and Electrical Resistance

Sheet resistance has the units of $\Omega/\square$. A separate instrument was used to measure the sheet resistance. Probe geometry also changed. An in-line equally spaced probe was used instead. The value of sheet resistance (R_s) and the electrical resistance are related.

$$R_{sheet} = 4.53 * R_{electrical} \quad \text{for the in-line probe} \quad (12)$$

$$R_{sheet} = 3.90 * R_{electrical} \quad \text{for the square probe} \quad (13)$$

3.3.3 Resistance and Resistivity

Resistivity reported in this thesis is in $\mu\Omega \text{ cm}$. The relationship between resistivity and sheet resistance was shown before in equation 3.

$$\rho = R_{sheet} * t$$

Where t is the corrected thickness. The oxidation or magnetic dead layer must be excluded. Since probe geometry is in-line lay-out, the resistivity is

$$\rho = 4.53 * R_{electrical} * t \quad (14)$$

3.3.4 Parallel Resistors Approximation

The underlayer influences the sheet resistance of a bilayer film. In order to determine the individual resistance of the top layer, a parallel resistance was assumed. $R_{\text{sheet}}(\text{total})$ is the measured resistance of the bilayer film made by contacting the probe to the top layer. $R_{\text{sheet}}(\text{UL})$ is the sheet resistance of the corresponding underlayer that was measured separately. $R_{\text{sheet}}(\text{top})$ is the calculated resistance of the top layer that was deposited on the underlayer. In this report, the calculated resistance of the top layer, $R_{\text{sheet}}(\text{top})$, is the value that was used to calculate the resistivity of that layer. This resistivity value will be used in the results and discussion section. Figure 17 show the schematic of the parallel resistance approximation. The parallel resistance relationship is shown below.

$$1/R_{\text{electrical}}(\text{total}) = 1/R_{\text{electrical}}(\text{top}) + 1/R_{\text{electrical}}(\text{UL}) \quad (15)$$

$$1/R_{\text{sheet}}(\text{total}) = 1/R_{\text{sheet}}(\text{top}) + 1/R_{\text{sheet}}(\text{UL}) \text{ is also true since } R_{\text{sheet}} = 4.53 * R_{\text{electrical}} \quad (16)$$

Figure 17. The parallel resistors approximation.

3.3.5 Anisotropic Resistivity ($\Delta\rho$)

There is no available instrument to measure $\Delta\rho$ directly. $\Delta\rho$ values reported here were calculated from the measured magnetoresistivity ratio ($\text{AMR} = \Delta R/R = \Delta\rho/\rho$) multiplied by the corresponding resistivity, as :

$$\Delta\rho = (\Delta\rho/\rho) * \rho = R_s * t \quad (17)$$

Where R_s was found from equation 17 to be:

$$R_s (\text{top}) = \{R_s (\text{total}) * R_s (\text{Underlayer})\} / \{R_s (\text{Underlayer}) - R_s (\text{total})\} \quad (18)$$

3.3.6 X-Ray Diffraction

The purposes of XRD study are to determined the grain size, crystal structure, and lattice parameter of a film. The positions of the diffraction pattern (Q_{peak}) correspond to the crystal structure (FCC, BCC, and HCP). Full Width at Half Maximum relates to the relative grain size of a film. The intensity tells the order of the film. The FWHM of each diffraction peak can be expressed by a convolution of functions describing instrument contribution such as x-ray diffraction optics and function specific to the sample's characteristic. The intensity can be described in a simple way as

$$\text{FWHM} = \text{Instrument Error} * \text{Grain Size Distribution} * \text{Strain Distribution} + \text{Background}.$$

Since the study films were polycrystalline, the physical imperfections such as grain size distribution and strain distribution can cause broadening of the diffraction peaks.

Assuming the inhomogeneous ($\Delta Q^2_{\text{inhomogeneous}}$) strain broadening³⁰ is $0.025\text{\AA}^{-1}$. The FWHM can be corrected to reflect only the grain size.

$$\Delta Q^2 = \text{FWHM}^2 - \Delta Q_{\text{inhomogeneous}}^2 \quad (19)$$

ΔQ is the peak width at half maximum caused by the grain size distribution. This ΔQ is the value that was used to determine the relative grain size for this entire thesis. The relationship between ΔQ and grain size is that grain size is inversely proportional to ΔQ . To determine the interplanar spacing d , the peak position was used in the calculation in equation 19. The peak position also reported in $\text{\AA}^{-1}$. The interplanar spacing is calculated by:

$$d = 2\pi / Q_{\text{peak}} \quad (20)$$

Where Q_{peak} is the position that reflection the interesting peak.

By using XRD results, the relative grain size (ΔQ) and the ordered (Intensity) of 150 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ with 50 $\text{\AA}$ Ta, with fixed underlayer thickness and composition, and without underlayer were compared. ΔQ and Intensities of 80 to 500 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ with fixed underlayers and with 50 $\text{\AA}$ Ta underlayer were compare as well.

Chapter 4

Results

4.1 Magnetic Transition

Saturated magnetic moments (B_s) of 500 Å $\text{NiFe}_{(1-x)}\text{Cr}_x$ and $\text{Ni}_{(1-x)}\text{Cr}_x$ were measured by using the conventional BH loop tracer. Typical data plots for $\text{NiFe}_{(1-x)}\text{Cr}_x$ and $\text{Ni}_{(1-x)}\text{Cr}_x$ alloys are shown in Figures 18 and 19 respectively. Chromium (x-wt%) was gradually added into $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and $\text{Ni}_{(1-x)}\text{Cr}_x$ alloy until the alloy reached the magnetic transition points. The magnetic moments of both films are linearly proportional to $(\text{Ni}_{80}\text{Fe}_{20})$ or Ni concentration in the alloys only in their ferromagnetic regions. B_s of $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ 500 Å appears to be a maximum at 1.7 nWb at zero chromium concentration (pure $\text{Ni}_{80}\text{Fe}_{20}$) and decreases to zero nW when chromium concentration reaches 25 wt%. This implies that $\text{Ni}_{80}\text{Fe}_{20}$, which is ferromagnetic, becomes nonmagnetic material at 25 wt% chromium addition. $\text{Ni}_{(1-x)}\text{Cr}_x$ has similar behavior. $\text{Ni}_{(1-x)}\text{Cr}_x$ 500 Å has maximum moment of 1.6 nWb at zero chromium concentration (pure Ni). Magnetic moment reduces as chromium concentration (x) is introduced into $\text{Ni}_{(1-x)}\text{Cr}_x$ alloy. It has zero saturated magnetic moment at 6 wt% chromium addition. Non-magnetic alloys in which chromium concentration is beyond 25 wt% for $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and 6.0 wt% for $\text{Ni}_{(1-x)}\text{Cr}_x$ system were chosen to be the starting concentration for potential underlayer study.

Figure 18. Saturated field measurements for 500 Å $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$.

Figure 19. Saturated field measurements for 500 Å $\text{Ni}_{(1-x)}\text{Cr}_x$.

4.2 Dependence of Electrical Resistivity (ρ) on Chromium Concentration in Monolayer Films (500 Å $\text{NiFe}_{(1-x)}\text{Cr}_x$ and 500 Å $\text{Ni}_{(1-x)}\text{Cr}_x$)

The resistivity was determined from sheet resistance (R_s), which was measured by a four-point probe. Figure 20 shows the plot of electrical resistivity of $\text{NiFe}_{(1-x)}\text{Cr}_x$ 500 Å and $\text{Ni}_{(1-x)}\text{Cr}_x$ 500 Å versus Cr concentration. For $\text{NiFe}_{(1-x)}\text{Cr}_x$, the resistivity for Cr concentrations between zero and 15 wt% Cr smoothly increases from 31 $\mu\Omega$ cm to 100

$\mu\Omega$ cm. Resistivity linearly increases for chromium concentrations between 15 and 65 wt%. Beyond 65 wt% chromium, resistivity smoothly decreases until resistivity reaches $80 \mu\Omega$ cm for 100% chromium. The resistivity data indicates that 500 Å films with chromium concentration between 0-15 wt% and 65-100 wt% follow Nordheim's rule.³⁰ In these two regions, the alloy is single phase, face centered cubic (FCC) and body centered cubic (BCC) respectively. Between 15 wt% and 65 wt% the x-ray diffraction spectra show that $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ is Hexagonal Close-Packed (HCP). The resistivity plots may be inconsistent with the X-ray spectra. The resistivity plot indicates that possibly mixed phases are present within this region.

The resistivity versus Cr concentration in $\text{Ni}_{(1-x)}\text{Cr}_x$ is similar to that in $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$. The $\text{Ni}_{(1-x)}\text{Cr}_x$ resistivity between 15 and 50 wt% Cr is almost identical to the resistivity of $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ system in the same Cr concentration range. The resistivity plots indicate that mixed phases may be present in this region as well as in that of $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ system.

The resistivities of pure $\text{Ni}_{80}\text{Fe}_{20}$, Cr, and Ni from these experiments are $30.65 \mu\Omega$ cm, $92.16 \mu\Omega$ cm, and $15.66 \mu\Omega$ cm respectively. These resistivities are higher than the published data for bulk $\text{Ni}_{80}\text{Fe}_{20}$ alloy, Cr, and Ni, which are $14 \mu\Omega$ cm²⁸ for $\text{Ni}_{80}\text{Fe}_{20}$, $12.9 \mu\Omega$ cm for Cr, and $6.9 \mu\Omega$ cm for Ni.³¹ Cr films deposited in these experiments appear to have resistivity seven times higher than bulk Cr compared to $\text{Ni}_{80}\text{Fe}_{20}$ alloy and Ni film, which have resistivity two to three times higher than bulk alloys. This may be due to the contamination in the sputtering chamber since 100 wt% Cr is always deposited last. Thin film resistivities are expected to be higher than bulk

is always deposited last. Thin film resistivities are expected to be higher than bulk resistivities due to two reasons. First, thin films have more defects, increasing the scattering. Electrons have more tendencies to scatter at grain boundaries and at the defects. Second, as the films' thickness decreases, surface scattering plays an important role.

Figure 20. The Electrical resistivity versus Cr concentration.

4.3 Dependence of Anisotropic Magnetoresistance ($\Delta R/R$) of $\text{Ni}_{80}\text{Fe}_{20}$ in Bilayer Films on Chromium Concentration in Underlayer

$\text{Ni}_{80}\text{Fe}_{20}$ films 150 Å thick were deposited on two different underlayer systems (45 Å thick) i.e. $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and $\text{Ni}_{(1-x)}\text{Cr}_x$. Anisotropic magnetoresistivities of $\text{Ni}_{80}\text{Fe}_{20}$ were measured at different underlayer Cr concentration (x). The plots of $\Delta R/R$ versus Cr wt% are shown in Figure 21 for $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ and Figure 22 for $\text{Ni}_{(1-x)}\text{Cr}_x$. From the results of Section 4.1 the underlayer composition was restricted to the

nonmagnetic region. For $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$, x was varied from 25 to 100%. $\Delta R/R$ shows a maximum when chromium reaches 44 wt% in $(\text{Ni}_{80}\text{Fe}_{20})_{(1-x)}\text{Cr}_x$ system. $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ for this specific composition is 3.5%. Compositions between 40 and 48 wt% Cr show the highest $\Delta R/R$. $\text{Ni}_{(1-x)}\text{Cr}_x$ underlayer shows similar behavior to $\text{NiFe}_{(1-x)}\text{Cr}_x$ system. There is a maximum in $\Delta R/R$ at 42 wt% Cr.

Figure 21. Dependence of $\Delta R/R$ on chromium concentration in the $\text{NiFe}_{1-x}\text{Cr}_x$ UL.

Figure 22. Dependence of $\Delta R/R$ on chromium concentration in the $\text{Ni}_{1-x}\text{Cr}_x$ UL.

4.4 Dependence of Electrical Resistivity (ρ) on Film Thickness for Monolayer Film

Single layer films were deposited with thicknesses of 40 Å to 800 Å. Chromium concentration (x) was fixed at 44 wt% in $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ and 42 wt% in $\text{Ni}_{1-x}\text{Cr}_x$, based on results of Section 4.3. Resistivities were determined from the sheet resistance shown in Figure 23. Resistivities of monolayer $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, $\text{Ni}_{80}\text{Fe}_{20}$, and Ta are plotted in Figure 24 a, b and c respectively. $\text{Ni}_{80}\text{Fe}_{20}$ films had the lowest resistivity. Ta films had substantially the highest resistivity; i.e. at 50 Å Ta resistivity is six times higher than that of $\text{Ni}_{80}\text{Fe}_{20}$. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ resistivity is greater than $\text{Ni}_{80}\text{Fe}_{20}$ but less than Ta resistivity. For example, at 50 Å, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ resistivity is four times higher than that of $\text{Ni}_{80}\text{Fe}_{20}$.

The resistivity results show the segregation of thickness into two regions, called the thin film and thick film regions. In the thick film region, film thickness is greater than 200 Å. Above 200 Å, the resistivity is independent of the film thickness and approaches the bulk value. The bulk resistivities are $14 \mu\Omega \text{ cm}^{28}$ for $\text{Ni}_{80}\text{Fe}_{20}$ and $169 \mu\Omega \text{ cm}^{32}$ for Ta. The thin region is where the thickness is less than 200 Å. For $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, Ta, and $\text{Ni}_{80}\text{Fe}_{20}$, the resistivity increases dramatically when film thickness decreased in this thin region.

Sheet resistance was converted to resistivity by using the relationship $\rho = R_s \cdot t$, where t is the film thickness, as described in Section 3.3. Figure 24 is a plot of resistivity versus thickness. Since films were exposed to the air after being unloaded, oxidation most likely occurred at the film surface, creating a thin dead layer on the film surface. The active thickness or the corrected thickness is the result of subtracting that thin dead

layer from the total physical thickness. The active thickness (corrected thickness or magnetic thickness) can be determined directly from B/H loop. The thickness of the films should be corrected to take the oxidized layer into account in this analysis; however, only permalloy thickness has been corrected. Although the sheet resistance in thin regions of Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ were strongly sensitive to their thickness, the use of Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ thickness without correcting is acceptable at the present under an assumption that Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ had a negligible oxidation rate.

Figure 23. Sheet resistance of mono-layer $\text{Ni}_{80}\text{Fe}_{20}$, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, and Ta film.

If the relative oxidation rate of Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ are more similar to that of $\text{Ni}_{80}\text{Fe}_{20}$, the conversion of sheet resistance to resistivities may not be exactly correct. The resistivity of both Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ films would be lower than that of the films

in Figure 24. The resistivity of NiFe is determined by taking the oxidation into account while the resistivity of Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ did not. As a result, $\text{Ni}_{80}\text{Fe}_{20}$ shows the lowest resistivity compared to Ta and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ film.

Figure 24. Resistivity of a) $\text{Ni}_{80}\text{Fe}_{20}$ film, b) $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ film, and c) Ta film.

4.5 Dependence of $\Delta R/R$ (or $\Delta\rho/\rho$), Resistivity and $\Delta\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ on Under Layer Thickness

4.5.1 $\text{Ni}_{80}\text{Fe}_{20}$ on $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ Underlayer

$(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ was chosen from the result of Section 4.3 because it has the highest $\Delta R/R$. $\text{Ni}_{80}\text{Fe}_{20}$ 120 Å was deposited on $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$. The $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer thickness was varied from zero Å to 80 Å. The $\Delta R/R$ is plotted in Figure 25. $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ increased as $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer thickness increased, and it reached the maximum of 3.6 % at 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer thickness. Beyond 45 Å, $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ started decreasing as $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer increased. When $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer reaches 80 Å, $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ coefficient dropped to 1.9%.

Figure 25. The Anisotropic Magnetoresistivity of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ in bilayer as a function of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer thickness.

Electrical resistivity of permalloy under the influence of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ was determined from the bilayer resistance by subtracting out the $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ monolayer

resistance. The conversion method was presented earlier in Section 3.3. Figure 26 shows the converted resistivity of Permalloy as a function of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ thickness. With no underlayer, the resistivity of the film, $33.57 \mu\Omega \text{ cm}$, is the resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ at $120 \text{ \AA}$. The resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ slowly decreases with increasing underlayer thickness to a minimum of $20.43 \mu\Omega \text{ cm}$, at $45 \text{ \AA}$ $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ thickness. This is the same thickness that the largest $\Delta R/R$ enhancement occurred. After passing the minimum, resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ increases as the underlayer thickness increases.

Anisotropic magnetoresistance, $\Delta\rho$, of bilayer $\text{Ni}_{80}\text{Fe}_{20}/(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ is shown in Figure 27. $\Delta\rho$ was determined by the method presented Section 3.3.5. At zero underlayer thickness, $\Delta\rho$ is $0.77 \mu\Omega \text{ cm}$. When $15 \text{ \AA}$ $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer is added, $\Delta\rho$ dropped to $0.55 \mu\Omega \text{ cm}$. $\Delta\rho$ increases as the underlayer thickness increases and reaches the maximum of $0.75 \mu\Omega \text{ cm}$ at $45 \text{ \AA}$ $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$. $\Delta\rho$ decreases to $0.55 \mu\Omega \text{ cm}$ at $80 \text{ \AA}$ underlayer thickness. At $45 \text{ \AA}$ underlayer thickness, $\text{Ni}_{80}\text{Fe}_{20}$ had the highest $\Delta\rho/\rho$, the highest $\Delta\rho$, and the lowest ρ . This implies that the same microstructure mechanism controls both $\Delta\rho$ and ρ of the $\text{Ni}_{80}\text{Fe}_{20}$ film.

Figure 26. Converted resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ as a function of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ UL thickness.

Figure 27. $\Delta \rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ as a function of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ UL thickness.

4.5.2 Ni₅₈Cr₄₂ Underlayer

The best $\Delta\rho/\rho$ ($\Delta R/R$) was found in Section 4.3 to be at x equals 42 wt% Cr for Ni_{1-x}Cr_x. At this composition, 3.5% $\Delta\rho/\rho$ was found. $\Delta\rho/\rho$ is plotted in Figure 28 as a function of Ni₅₈Cr₄₂ thickness. $\Delta\rho/\rho$ of Ni₈₀Fe₂₀ with 20 Å Ni₅₈Cr₄₂ underlayer is 2.5%. $\Delta\rho/\rho$ of Ni₈₀Fe₂₀ increased as Ni₅₈Cr₄₂ underlayer thickness increases and reaches the maximum 3.5% at 45 Å Ni₅₈Cr₄₂ underlayer thickness. Ni₅₈Cr₄₂ critical thickness was the same as (Ni₈₀Fe₂₀)₅₆Cr₄₄ thickness. $\Delta\rho/\rho$ decreases as Ni₅₈Cr₄₂ underlayer increases. $\Delta\rho/\rho$ dropped to 1.86% when Ni₅₈Cr₄₂ reached 80 Å.

Figure 28. The Anisotropic Magnetoresistivity of 120 Å Ni₈₀Fe₂₀ as a function of Ni₅₈Cr₄₂ underlayer thickness.

Figure 29 shows the resistivity of Permalloy as a function of $\text{Ni}_{58}\text{Cr}_{42}$ underlayer thickness. At zero Å underlayer, resistivity of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ is 33.57 $\mu\Omega$ cm. The resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ reached the minimum at 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ thickness, which is at the same critical thickness as $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer. The resistivity at this point is 20.46 $\mu\Omega$ cm. This underlayer thickness results in the largest enhancement of $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ in bilayer film. $\Delta\rho$ of bilayer $\text{Ni}_{80}\text{Fe}_{20}$ with $\text{Ni}_{58}\text{Cr}_{42}$ underlayer is shown in Figure 30. Both $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ showed similar behavior.

Figure 29. Converted resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ as a function of $\text{Ni}_{58}\text{Cr}_{42}$ underlayer thickness.

Figure 30. $\Delta \rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ as a function of $\text{Ni}_{58}\text{Cr}_{42}$ underlayer thickness.

4.6 Dependence of $\Delta\rho/\rho$ and Resistivity (ρ) of $\text{Ni}_{80}\text{Fe}_{20}$ on $\text{Ni}_{80}\text{Fe}_{20}$ Thickness with Fixed Underlayer Thickness and Composition

4.6.1 Anisotropic Magnetoresistive Ratio ($\Delta R/R$) of $\text{Ni}_{80}\text{Fe}_{20}$ Film in Bilayer System

In a bilayer film with fixed underlayer thickness, $\text{Ni}_{80}\text{Fe}_{20}$ films were deposited on the top. The underlayers are 50 Å Ta, 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, or 45 Å $\text{Ni}_{58}\text{Cr}_{42}$. The thicknesses of $\text{Ni}_{80}\text{Fe}_{20}$ was varied from 50 Å to 450 Å. The effects of $\text{Ni}_{80}\text{Fe}_{20}$ thickness on AMR ratios of $\text{Ni}_{80}\text{Fe}_{20}$ were investigated and are presented in Figure 31. The bottom curve (diamonds) is for a monolayer $\text{Ni}_{80}\text{Fe}_{20}$ film. Single layer $\text{Ni}_{80}\text{Fe}_{20}$ was deposited at different thickness from 45 Å to 450 Å. All thicknesses used in the plot have been corrected as presented earlier in Section 3.3. At all $\text{Ni}_{80}\text{Fe}_{20}$ thickness, $\Delta\rho/\rho$ is highest

when an underlayer of either $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ is used. $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer increases with the $\text{Ni}_{80}\text{Fe}_{20}$ thickness.

Table V shows the summary of results. At about 120 Å $\text{Ni}_{80}\text{Fe}_{20}$, $\Delta\rho/\rho$ is 3.61% for 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer, and $\Delta\rho/\rho$ is 3.47% for 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ underlayer. $\Delta\rho/\rho$ for 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ with 50 Å Ta underlayer and without underlayer are 2.5% and 1.76% respectively. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer produced similar $\Delta\rho/\rho$ properties. $\text{Ni}_{80}\text{Fe}_{20}$ appeared to be very sensitive to the thickness especially in the thin region. For the thicker films, $\text{Ni}_{80}\text{Fe}_{20}$ films with and without underlayer shows less sensitivity to the film thickness.

Table V. Summary of AMR results.

	Best Underlayer		$\text{Ni}_{80}\text{Fe}_{20}$			
	Cr wt %	Thickness (Å)	Thickness (Å)	$\Delta\rho/\rho$ (%)	ρ ($\mu\Omega$ cm)	$\Delta\rho$ ($\mu\Omega$ cm)
$(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$	44	45	~120	3.60	20.44	0.74
$\text{Ni}_{58}\text{Cr}_{42}$	42	45	~120	3.47	20.60	0.71
Ta	-	50	~120	2.5	27.0	0.61
$\text{Ni}_{80}\text{Fe}_{20}$	-	-	~123	1.76	33.20	0.77

Figure 31. Anisotropic magnetoresistance of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer vs. $\text{Ni}_{80}\text{Fe}_{20}$ thickness

4.6.2 Resistivity (ρ)

Resistivities of $\text{Ni}_{80}\text{Fe}_{20}$ with different underlayers are compared in Figure 32. The resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ without underlayers is 1.2 times larger than with Ta underlayer and 1.6 times larger than with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, or $\text{Ni}_{58}\text{Cr}_{42}$ underlayer. As seen in Table V, for about the same Permalloy thickness, the values are $33.2 \mu\Omega \text{ cm}$ for $\text{Ni}_{80}\text{Fe}_{20}$ with no underlayer and $20.44 \mu\Omega \text{ cm}$ for $\text{Ni}_{80}\text{Fe}_{20}$ with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer. Resistivity of bare $\text{Ni}_{80}\text{Fe}_{20}$ increases as the thickness decreases. In the thick film region ($t > 200 \text{ \AA}$), the resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer is thickness independent. In the thin film region ($t < 200 \text{ \AA}$), resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ without underlayer shows the most sensitivity to thickness. The use of a Ta underlayer reduced the $\text{Ni}_{80}\text{Fe}_{20}$

resistivity with slight changes to $\text{Ni}_{80}\text{Fe}_{20}$ sensitivity. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer show the capability of dramatically reducing $\text{Ni}_{80}\text{Fe}_{20}$ resistivity from $33.2 \mu\Omega \text{ cm}$ to $20.44 \mu\Omega \text{ cm}$ for $120 \text{ \AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer, and decreasing the sensitivity to $\text{Ni}_{80}\text{Fe}_{20}$ thickness. Bare $\text{Ni}_{80}\text{Fe}_{20}$ resistivities shown in Figures 32 and 24 are identical data.

Figure 32. Resistivity of Permalloy film with and without underlayer versus Permalloy thickness.

4.6.3 Anisotropic Resistivity ($\Delta\rho$)

Figure 33 shows the comparison of $\Delta\rho$ in $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer. Anisotropic resistivity ($\Delta\rho$) is the product of $(\Delta\rho/\rho)$ and ρ as shown in Section 3.3. $\Delta\rho$ depends on $\text{Ni}_{80}\text{Fe}_{20}$ thickness and increases as $\text{Ni}_{80}\text{Fe}_{20}$ thickness increases. $\Delta\rho$ in thin

film region was more thickness sensitive than $\Delta\rho$ in thick film region. Tantalum underlayer does not change the anisotropic resistivity ($\Delta\rho$) of $\text{Ni}_{80}\text{Fe}_{20}$ film while $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer significantly change $\Delta\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ films. For instance as seen in Figure 33, $\Delta\rho$ of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ film with and without Ta was about 0.61 and 0.58 $\mu\Omega\text{ cm}$. Using $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer, $\Delta\rho$ increases to 0.71 $\mu\Omega\text{ cm}$. $\Delta\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer is more sensitive to the thickness in thin film region, which is also true for ρ as described in Section 4.6.3.

Figure 33. The anisotropic resistivity ($\Delta\rho$) of Permalloy with and without underlayers.

4.7 Magnetic Properties

Coercivity force (H_c) for $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayers is plotted in Figure 34. H_c of $\text{Ni}_{80}\text{Fe}_{20}$ films is proportional to thickness, in thin film region. For the thick film region, H_c showed no dependence on the thickness. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$

underlayer has no effect on H_c property of Permalloy. These results support the objective of using underlayers to enhance the anisotropic resistivity without changing any other magnetic properties.

Anisotropic field (H_k) was the other value used to observe the magnetic properties.

Figure 35 shows the anisotropic field (H_k) of $Ni_{80}Fe_{20}$ with and without underlayer.

H_k did not show any dependence on the thickness of $Ni_{80}Fe_{20}$. The use of underlayers had no clear effect on the H_c and H_k of $Ni_{80}Fe_{20}$ film.

Figure 34. Coercivity Force (H_c) of $Ni_{80}Fe_{20}$ with and without underlayer.

Figure 35. Anisotropic Field (H_k) of $Ni_{80}Fe_{20}$ with and without underlayers.

4.8 Summary of Results

In summary, both 45 Å $(Ni_{80}Fe_{20})_{56}Cr_{44}$ underlayer and $Ni_{58}Cr_{42}$ underlayer have been shown to significantly enhance the anisotropic magnetoresistance ratio ($\Delta R/R$) of permalloy. The enhancement is due to the resistivity (ρ) decrease and the anisotropic resistivity increase. In addition, neither underlayer changes the coercivity or anisotropic field of the $Ni_{80}Fe_{20}$ film. However the electrical and magnetic measurements do not explain why these underlayers have such a strong effect. To understand the reasons, a microstructure investigation was done and is presented in Chapter 5.

Chapter 5

X-ray Diffraction Analysis

The purpose of the X-ray Diffraction Analysis (XRD) study was to determine the crystal structure and microstructure of $\text{Ni}_{80}\text{Fe}_{20}$ in monolayer and bilayer films. Full width at half maximum (FWHM) of the observed peak is due to both the broadening of the diffraction line caused by instrument error and physical imperfections such as strain and grain size distribution. FWHM is inversely proportional to grain size. Assuming that the broadening line due to the instrument error is zero, ΔQ is the approximate FWHM after subtracting the broadening due to non-uniform strain. The non-uniform strain³⁰ is assumed to be $0.025 \text{ \AA}^{-1}$. As discussed in Section 3.3.6, the corrected FWHM is $\Delta Q = (\text{FWHM}^2 - 0.025^2)^{1/2}$.

The predominant peak observed from out-of-plane diffraction can provide the interplanar spacing, d , since $d = 2 \pi / Q_{\text{pk}}$. Q_{pk} is the position of the diffracted peak in $\text{\AA}^{-1}$. Lattice constant is determined by $d^*(h^2 + k^2 + l^2)^{1/2}$, where (h, k, l) is the corresponding reciprocal lattice of that peak. On the other hand, the in-plane lattice constant is determined by the corresponding predominant in-plane peak position. ΔQ in-plane contains the grain size information that was previously presented in Section 3.3.6.

5.1 Monolayer of $\text{Ni}_{80}\text{Fe}_{20}$

Both in-plane and out-of-plane diffraction patterns for 90 $\text{\AA}$ to 300 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ were observed. Figure 36 shows the observation of out-of-plane (111) peak of 300 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$. This (111) peak in $\text{Ni}_{80}\text{Fe}_{20}$ indicates a poor orientation in the film due to the

weak and broad (111) peak. The in-plane diffraction spectrum is shown in Figure 37. Strong (111) and weak (200) and (220) peaks are reflected. These $\text{Ni}_{80}\text{Fe}_{20}$ spectra correspond to an FCC phase with a weak (111) intensity distribution and stacking fault on (200) judging from the peak broadening compared to (111) and (220) peak width (ΔQ). The absolute (111) peak intensities (in counts per second) of $\text{Ni}_{80}\text{Fe}_{20}$ are shown in Table VI. Intensity was significantly increased when the film thickness increased. This is due to the larger amount of $\text{Ni}_{80}\text{Fe}_{20}$ (in thick film) which can diffract stronger than in thinner film. In addition, the growth of thicker film has better crystal orientation than the thinner film.

Figure 36. 300 Å NiFe (111) out-of-plane reflection.

Figure 37. 300 Å $\text{Ni}_{80}\text{Fe}_{20}$ (111), (200), and (220) in-plane reflection.

5.2 Monolayer $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$

Both out-of-plane and in-plane XRD of 80 Å to 500 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ (wt%) were investigated. Figure 38 shows the observation of 200 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ (wt%) out-of-plane (002) peak. There was a single strong HCP (002) peak reflection from the out-of-plane spectra corresponding to $d = 2.065$ Å. Figure 39 is the in-plane reflection. The in-plane diffraction shown in $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ shows a well ordered HCP phase due to the presence of (100) and (110) reflections with a preferred (002) orientation along the growth direction (c-axis). Table VII shows the summary of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ spectra. In the present experiment, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ greater than 90 Å formed HCP structure with growth texture in (002) direction. This is possibly due to the growing $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ film seeking to minimize its surface free energy, and the close-packed plane with the lowest surface energy of HCP is the (002) plane. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ deposited by the same

deposition technique thinner than 90 Å was reported to be poorly ordered BCC structure with a high stacking fault density, with the corresponding inter-planar spacing normal to the growth direction (110) equal to 2.070 Å.³¹ For $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, ΔQ is opposite to that of $\text{Ni}_{80}\text{Fe}_{20}$. ΔQ of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ is directly proportional to the film thickness for the (110) and the (101) peaks, and ΔQ of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ inversely proportional to film thickness for the (002) peak, as shown in table VII.

Since ΔQ is inversely proportional to the in-plane grain size, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ in-plane, (110) direction, grain size appears to decrease when the thickness increases.

Figure 38. 200 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ (002) out-of-plane reflection.

Figure 39. 200 Å $(\text{Ni}_{80}\text{Fe}_{20})\text{Cr}_{44}$ (110), and (100) in-plane reflection.

Table VI. (111) Intensity of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer

$\text{Ni}_{80}\text{Fe}_{20}$ Thickness (Å)	(111) Intensity (cps)		
	$\text{Ni}_{80}\text{Fe}_{20}$	w/Ta UL	w/ $\text{Ni}_{58}\text{Cr}_{42}$ UL
90	weak	700	1800
130			4500
150	10	2900	6100
200			12000
230		5800	
250			
300	30	7400	20000
400			25000

Table VII. Out-of-plane and in-plane summary of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ (wt%)

Thickness (Å)	(002) Out-of-Plane		(100) In-Plane		(110) In-Plane		(101) In-Plane	
	Intensity (cps)	ΔQ (Å ⁻¹)	Intensity (cps)	ΔQ (Å ⁻¹)	Intensity (cps)	ΔQ (Å ⁻¹)	Intensity (cps)	ΔQ (Å ⁻¹)
80	154	.083	6.8	.030	17.4	.025	16.25	.013
120	375	.054	7	.035	20	.033		
200	1022	.029	7	.043	26	.048	76	.071
500			47	.038	20	.055	146	.082

Table VIII. Out-of-plane (101) summary

NiFe Thickness (Å)	$\Delta Q \text{ Ni}_{80}\text{Fe}_{20}$ (101) (Å ⁻¹)			$\text{Ni}_{80}\text{Fe}_{20}$ (101) Intensity (cps)		
	$\text{Ni}_{80}\text{Fe}_{20}$ (111)	w/Ta (101)	w/ $\text{Ni}_{58}\text{Cr}_{42}$ (101)	$\text{Ni}_{80}\text{Fe}_{20}$ (111)	w/Ta (101)	w/ $\text{Ni}_{58}\text{Cr}_{42}$ (101)
90	0.117	0.058	0.033	8	110	185
130			0.027			481
150		0.046	0.024		212	514
200						
230		0.042			380	
250	0.088			21		
300	0.090	0.040	0.018	25	500	1190
400			0.016			1573

Table IX. In-plane summary

$\text{Ni}_{80}\text{Fe}_{20}$ Thickness (Å)	$\Delta Q \text{ Ni}_{80}\text{Fe}_{20}$ (101) (Å ⁻¹)			$\text{Ni}_{80}\text{Fe}_{20}$ Intensity (cps)		
	$\text{Ni}_{80}\text{Fe}_{20}$ (220)	w/Ta (101)	w/ $\text{Ni}_{58}\text{Cr}_{42}$ (101)	$\text{Ni}_{80}\text{Fe}_{20}$ (220)	w/Ta (101)	w/ $\text{Ni}_{58}\text{Cr}_{42}$ (101)
90		0.082	0.061		18	29
130			0.055			50
150		0.077	0.053		30	59
200			0.046			90
230		0.069			54	
250	0.11	0.069		3		
300	0.112	0.067	0.044	2.5	57	108
400			0.039			132

5.3 Bilayer $\text{Ni}_{80}\text{Fe}_{20}$ with 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ underlayer

Forty five Å $\text{Ni}_{58}\text{Cr}_{42}$ / 90 Å to 400 Å $\text{Ni}_{80}\text{Fe}_{20}$ bilayer films were investigated. The diffraction pattern of $\text{Ni}_{80}\text{Fe}_{20}$ for out-of-plane showed strong (111) peak compared to monolayer $\text{Ni}_{80}\text{Fe}_{20}$ film. Figure 40 shows 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ / 300 Å $\text{Ni}_{80}\text{Fe}_{20}$. This strong (111) peak indicates a well oriented film with preferred texture in (111) normal to the film surface. As a result of the $\text{Ni}_{58}\text{Cr}_{42}$ underlayer, (111) reflection of $\text{Ni}_{80}\text{Fe}_{20}$ is about two orders of magnitude greater than for $\text{Ni}_{80}\text{Fe}_{20}$ without an underlayer (Figure 36). The (111) intensities are summarized in Table VI, for $\text{Ni}_{80}\text{Fe}_{20}$ films with and without underlayers. Table VIII shows the out-of-plane in (101) direction. The (101) peak intensities of $\text{Ni}_{80}\text{Fe}_{20}$ increase with the thickness regardless of underlayers.

The in-plane diffraction spectrum for this bilayer system presents a single sharp (110) peak. This sharp (110) peak indicates a strong (111) texture that is consistent with the out-of-plane reflection data. A (101) peak out-of-plane also presented. This is confirmation that the $\text{Ni}_{80}\text{Fe}_{20}$ film with the underlayer still maintained an FCC structure. Table IX shows the change of in-plane ΔQ of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer. For example, ΔQ in-plane of 300 Å $\text{Ni}_{80}\text{Fe}_{20}$ with underlayer is 0.044 Å^{-1} , which is three times smaller than ΔQ in-plane of 300 Å $\text{Ni}_{80}\text{Fe}_{20}$ without underlayer that is 0.112 Å^{-1} . Since ΔQ and grain size are inversely proportional, this XRD result indicates that the $\text{Ni}_{58}\text{Cr}_{42}$ underlayer increases the grain size of the $\text{Ni}_{80}\text{Fe}_{20}$ film.

In this bilayer system with $\text{Ni}_{58}\text{Cr}_{42}$ underlayer, ΔQ of (110) in $\text{Ni}_{80}\text{Fe}_{20}$ decreases with an increase in $\text{Ni}_{80}\text{Fe}_{20}$ thickness. This indicates that $\text{Ni}_{80}\text{Fe}_{20}$ in-plane grain size also increases as the film grows thicker.

Figure 40. 45 $\text{\AA}$ $\text{Ni}_{58}\text{Cr}_{42}$ / 300 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ (111) out-of-plane reflection.

Figure 41. 45 $\text{\AA}$ $\text{Ni}_{58}\text{Cr}_{42}$ / 300 $\text{\AA}$ $\text{Ni}_{80}\text{Fe}_{20}$ (110) in-plane reflection.

5.4 Bilayer $\text{Ni}_{80}\text{Fe}_{20}$ with 50 Å Ta underlayer

Figure 42 is the (111) reflection of 300Å $\text{Ni}_{80}\text{Fe}_{20}$ with 50 Å Ta underlayer. The XRD spectra of 50 Å Ta / 90 Å to 400 Å $\text{Ni}_{80}\text{Fe}_{20}$ was investigated. These films displayed strong (111) peak but less strong than with $\text{Ni}_{58}\text{Cr}_{42}$ underlayer (Figure 41). (111) intensities of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayers are shown in Table VI. With Ta underlayer, the (111) intensity increases approximately by two orders of magnitude, which is similar but less strong than with $\text{Ni}_{58}\text{Cr}_{42}$ underlayer. Figure 43 shows the in-plane diffraction pattern. Strong (110) peak of $\text{Ni}_{80}\text{Fe}_{20}$ is observed and a weak (002) peak belongs to Ta underlayer. With Ta underlayer, as thickness of $\text{Ni}_{80}\text{Fe}_{20}$ increases the ΔQ of (110) peak decreases, indicating that $\text{Ni}_{80}\text{Fe}_{20}$ in-plane grain size does increase with the $\text{Ni}_{80}\text{Fe}_{20}$ thickness.

Figure 42. 50 Å Ta/ 300Å $\text{Ni}_{80}\text{Fe}_{20}$ (111) peak out-of-plane.

Figure 43. 50 Å Ta / 300 Å $\text{Ni}_{80}\text{Fe}_{20}$ (110) peak in-plane.

5.5 XRD Summary

In summary, Table VI shows that Ta underlayer improves (111) texture of $\text{Ni}_{80}\text{Fe}_{20}$. The intensities increase by two orders of magnitude. With $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer, the (111) substantially improves. The intensities of $\text{Ni}_{80}\text{Fe}_{20}$ with the underlayer increase by three orders of magnitude.

Table VII shows the diffraction pattern for a monolayer of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$. The pattern is consistent with an HCP structure; therefore, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ is most likely an HCP structure. Table VIII and IX show the full width at half maximum (ΔQ) decrease as Ta or $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer are added to the $\text{Ni}_{80}\text{Fe}_{20}$. The decrease implies that grain size of $\text{Ni}_{80}\text{Fe}_{20}$, for both in-plane and out-of-plane direction, increase as underlayer is added. All of this implies that the improvement in $\Delta\rho$ and the reduction in ρ are due to the enhanced $\langle 111 \rangle$ texture and increased grain size in $\text{Ni}_{80}\text{Fe}_{20}$ as a result of its growth on the Ta or $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayers.

Chapter 6

Discussion

6.1 Cr Effects on Electrical and Magnetic Properties of $\text{Ni}_{80}\text{Fe}_{20}$ and Ni

The common property needed for an alloy to be used as an underlayer of $\text{Ni}_{80}\text{Fe}_{20}$ is that it must be nonmagnetic. Figures 18 and 19 proved that the alloys which have Cr in weight percent greater than 25% for $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ and 6 % for $\text{Ni}_{1-x}\text{Cr}_x$ system are nonmagnetic.

The dependence of the resistivity on the Cr composition for $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ shown in Figure 20 suggests that between zero and 12 wt% Cr, the $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ is a single phase alloy, most likely FCC. Therefore, resistivity increases with the concentration of Cr by Nordheim's rule. Beyond 65 wt% Cr, a second phase, possibly BCC, is formed. Figure 20 also suggests that the rule of mixtures is obeyed between 12 wt% and 65 wt% Cr. The linear relation between resistivity and Cr concentration in this range supports the rule of mixtures and implies that two phases were formed. However, the x-ray spectra of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ showed a predominantly HCP structure.

The previous work done by Lee and Toney *et al.*³³ showed a BCC phase of 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$. The inconsistency of the results may be due to size of the incident beam used for XRD and the inhomogeneity of the film composition. In this work, if the beam is less than the grain diameter, XRD data may depend on which grain the beam is incident. For the case of the small beam size, any inhomogeneity of the film compositions could result in a different diffraction pattern for different observation position on the film surface. If more than one phase is present, both phases may not be probed. In addition,

the investigations were done at different thickness. Resistivity versus Cr concentration was measured for 500 Å film, XRD in the thesis was done on a 200 Å film, and XRD by Lee and Toney *et al.*³³ was done on a 45 Å film. The difference in film thickness may have caused inconsistent results. The optimal $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ results from using a 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ underlayer and it is not yet clear what the $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ structure is at this film thickness.

6.2 Lattice Misfit

One question to be answered is why the underlayer influences the (111) texture of the $\text{Ni}_{80}\text{Fe}_{20}$. There is a possibility of good lattice matching between $\text{Ni}_{80}\text{Fe}_{20}$ and the underlayer. Table X shows the summary of structure and lattice parameters, which was done in this work and by others.³⁴⁻³⁶ For bilayer films, the matching between the two adjacent layers is important.

Table X. Structure and Lattice parameter of Ni, Cr, Ta, $\text{Ni}_{80}\text{Fe}_{20}$, $\text{Ni}_{58}\text{Cr}_{42}$, and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$

Material	Ni	Cr	Ta	$\text{Ni}_{80}\text{Fe}_{20}$ 120Å	$\text{Ni}_{58}\text{Cr}_{42}$ 80 Å	$(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ 200Å
Structure (Texture)	FCC (111)	BCC (110)	BCC (110)	FCC (111)	BCC (110)	HCP (002)
Bond Distance in Close-Packed Direction (Å)	2.4920 ³⁶	2.489 ³⁶	2.85 ³⁶	2.4910 ³⁶	—	—
Lattice Parameter (Å)	3.517 ³⁴	2.885 ³⁴	3.30 ³⁵	3.5378 {this work}	3.566 ³⁵	a=2.545, C=6.054 {this work}

Good matching can reduce stress and peeling of the film. Suppose that good lattice matching also is one of the mechanisms for the enhancement of $\Delta R/R$ in $\text{Ni}_{80}\text{Fe}_{20}$ film, the misfit is considered. The misfit is the difference between the interatomic distance in the matching planes along the matching direction.

We assume the lattice match is $\text{Ni}_{80}\text{Fe}_{20} (111)\langle 101 \rangle \parallel (\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44} (002)\langle 001 \rangle$, the reported atomic distance in $\text{Ni}_{80}\text{Fe}_{20}$ (FCC) on (111) plane along $\langle 101 \rangle$ direction is 2.4910 Å.³² The atomic distance of $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ on (002) plane along $\langle 001 \rangle$ direction from XRD is 2.545 Å. Misfit can be calculated in the following way. The lattice mismatch is then: $\varepsilon = |2.491 - 2.545| / 2.491 = 2.17\%$. Therefore, the misfit of $\text{Ni}_{80}\text{Fe}_{20} (111)\langle 101 \rangle \parallel (\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44} (002)\langle 001 \rangle$ is very small. It is most likely to be the situation.

For monolayer $\text{Ni}_{58}\text{Cr}_{42}$ and Ta, no XRD observation was made in this thesis. Lattice parameters for $\text{Ni}_{58}\text{Cr}_{42}$ and Ta refer to the previous study.³⁵ If $\text{Ni}_{58}\text{Cr}_{42}$ and Ta are both BCC, and if films grow with (110) texture, the matching distance along $\langle 100 \rangle$ direction and on (110) plane for $\text{Ni}_{58}\text{Cr}_{42}$ would be 3.566 Å⁴² and for Ta would be 3.303 Å. The misfit for $\text{Ni}_{80}\text{Fe}_{20} (111)\langle 101 \rangle \parallel \text{Ta} (110)\langle 100 \rangle$, is then:

$\varepsilon = |2.4910 - 3.303| / 2.4910 = 32.60\%$. The misfit for $\text{Ni}_{80}\text{Fe}_{20} (111)\langle 101 \rangle \parallel \text{Ni}_{58}\text{Cr}_{42} (110)\langle 100 \rangle$ is $|2.4910 - 3.566| / 2.4910 = 43.15\%$. This is very large mismatch and unlikely to be the situation.

If $\text{Ni}_{58}\text{Cr}_{42}$ and Ta are BCC, and films grow with (111) texture instead, the matching distance along $\langle 111 \rangle$ direction and on (110) plane of $\text{Ni}_{58}\text{Cr}_{42} (110)\langle 111 \rangle$ would be 2.52 Å, and 2.856 Å for Ta. In that case, the NiFe/Ta misfit is then:

$\varepsilon = |2.4910 - 2.256| / 2.4910 = 9.43\%$. The misfit for $\text{Ni}_{80}\text{Fe}_{20} / \text{Ni}_{58}\text{Cr}_{42}$ is $\varepsilon = |2.4910 - 2.520| / 2.4910 = 1.16\%$. This suggests that $\text{Ni}_{58}\text{Cr}_{42}$ and Ta may possibly grow (111) texture instead of (110) texture since the matching is more consistent with the enhanced $\Delta R/R$ of $\text{Ni}_{80}\text{Fe}_{20}$ in bilayer film with $\text{Ni}_{58}\text{Cr}_{42}$ and Ta underlayers.

The misfit calculation does not explain why there is an optimum thickness of underlayer. More XRD on $\text{Ni}_{58}\text{Cr}_{42}$ and Ta would be useful in understanding the enhancement mechanism.

6.3 Resistivity of $\text{Ni}_{80}\text{Fe}_{20}$, Ta, and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ film vs. their Thickness

As seen in Figure 24, resistivity increases very rapidly with the decrease of film thickness in thin film region (less than 200 Å). The resistivity data confirms the resistivity model introduced by Mayada *et al.*²⁸ When the mean free path of free electrons in bulk material is comparable to the film thickness, the increase of the resistivity is due to the decrease of mean free path. The mean free path of electrons in bulk $\text{Ni}_{80}\text{Fe}_{20}$ is 225 Å.²⁸

6.4 $\text{Ni}_{45}\text{Fe}_{11}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ thickness

The presence of the underlayer substantially enhances the $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$. As seen in Figures 25 and 28 for $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ respectively, the critical thickness for these Cr alloy underlayers is approximately 45 Å. For the underlayers that are thinner than 45 Å, $\Delta\rho/\rho$ increases with the underlayer thickness. This is due to the simultaneous decrease in ρ and the increase in $\Delta\rho$ in $\text{Ni}_{80}\text{Fe}_{20}$ film. In addition, XRD data shows the

tremendous increase in (111) intensity after using 50 Å Ta, 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ ³³ and 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ underlayer compared to $\text{Ni}_{80}\text{Fe}_{20}$ film without any underlayer. This indicates that (111) $\text{Ni}_{80}\text{Fe}_{20}$ is well oriented after the use of 50 Å Ta, 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ underlayer.

For the underlayers thicker than 45 Å, $\Delta\rho/\rho$ decreases with increase in underlayer thickness. There are several reasons for the drop in $\Delta\rho/\rho$ in these regions. First, the simultaneous increase in resistivity and decrease in $\Delta\rho$. Second, consider the amount of electrical current flowing through the film, bilayer films behave as two resistors connected in parallel. When the underlayer thickness is comparable to the $\text{Ni}_{80}\text{Fe}_{20}$ thickness, electrical resistance is dependent on underlayer film cross section (area times the film thickness). The higher the thickness the more current can flow through the underlayer; therefore, current shunting occurs, increasing the calculated resistance of the $\text{Ni}_{80}\text{Fe}_{20}$. The maximum improvement to the $\text{Ni}_{80}\text{Fe}_{20}$ microstructure occurs at 45 Å. Above that, current shunting dominates the results.

$(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ (wt%) control the structure of $\text{Ni}_{80}\text{Fe}_{20}$. As seen clearly from (111) enhancements of $\text{Ni}_{80}\text{Fe}_{20}$ with and without the underlayer, $\text{Ni}_{80}\text{Fe}_{20}$ without the underlayers shows poor ordering in (111) plane. With the underlayer, (111) texture is significantly enhanced.

6.5 $\Delta\rho/\rho$ Enhancement and the Underlayers

The study shows that the underlayers enhance the $\Delta\rho/\rho$ of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ up to 3.5%. These are due to the decrease in $\text{Ni}_{80}\text{Fe}_{20}$ resistivity and increase in $\Delta\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$.

Resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ decreases about 50% from that of $\text{Ni}_{80}\text{Fe}_{20}$ without underlayer. The substantial drop is due to grain size effects, which results in grain boundary scattering and surface scattering of the conduction electrons. Resistivity increases with the film thickness, which can be seen clearly in $\text{Ni}_{80}\text{Fe}_{20}$ with and without Ta underlayer (Figure 31). For $\text{Ni}_{80}\text{Fe}_{20}$ that is thicker than 200 Å, the decrease of $\text{Ni}_{80}\text{Fe}_{20}$ resistivity is due to grain size enlargement, which becomes longer than the electron mean free path. When the film thickness is larger than electron mean path, the electrical transport properties are then the bulk material properties. Thicker films also contain fewer defects, and the film is well ordered. In the thin region, which is less than 200 Å, film resistivity increases rapidly. This is because electron mean free path becomes comparable to the grain size. The electron mean free path of $\text{Ni}_{80}\text{Fe}_{20}$ is approximately 225 Å²⁸ calculated by using Fuchs' theory.

The results in Table VII, VIII, and IX showed that, as the $\text{Ni}_{80}\text{Fe}_{20}$ film becomes thicker, the FWHM of that film becomes narrower. Since grain size is inversely proportional to the FWHM, this implies that a thick film has a larger grain size compared to a thinner film. The data in Figure 32 is consistent with the work of Mayada *et al.*²⁸ which showed that the resistivity in thin films substantially increases as the thickness decreases. In addition, increased grain size leads to lowered resistivity of the film. With the underlayer, $\text{Ni}_{80}\text{Fe}_{20}$ resistivity decreases substantially. Thus, the underlayers assisted $\text{Ni}_{80}\text{Fe}_{20}$ to increase the grain size, as the result, the resistivity of $\text{Ni}_{80}\text{Fe}_{20}$ decrease. The underlayer has clearly influenced the growth of $\text{Ni}_{80}\text{Fe}_{20}$ film.

XRD results show that $\text{Ni}_{45}\text{Fe}_{11}\text{Cr}_{44}$ and $\text{Ni}_{52}\text{Cr}_{42}$ underlayer controlled the (111) texture of $\text{Ni}_{80}\text{Fe}_{20}$. As seen in Table VI the strong (111) presents after using the $\text{Ni}_{45}\text{Fe}_{11}\text{Cr}_{44}$ and $\text{Ni}_{52}\text{Cr}_{42}$ underlayers. The (111) peak intensities increase up to two orders of magnitude after using the underlayer. For the in-plane observation, FWHM of $\text{Ni}_{80}\text{Fe}_{20}$ decrease to 75% of FWHM of $\text{Ni}_{80}\text{Fe}_{20}$ without any underlayer. It implies that $\text{Ni}_{80}\text{Fe}_{20}$ with underlayer has well ordered and larger grain size than $\text{Ni}_{80}\text{Fe}_{20}$ without the underlayer. The resistivity model was used to explain the mechanism. The increased grain size leads to a longer mean free path of electron. $\Delta\rho/\rho$ shows distinct increase with the increase in grain size. The enhancement in $\Delta\rho/\rho$ with the help of $\text{Ni}_{58}\text{Cr}_{42}$, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or Ta underlayer is due to the decrease in resistivity which resulted from the larger grain size of $\text{Ni}_{80}\text{Fe}_{20}$. The great enhancement is substantial especially in thin $\text{Ni}_{80}\text{Fe}_{20}$ region. This is due to the size effect, which is consistent with Fuchs' theory.

In the thin region, the electron mean free path becomes comparable to the in-plane grain size, which means that the scattering at grain boundaries and surfaces has large contribution to scattering mechanism. The enhancement of $\Delta\rho/\rho$ for $\text{Ni}_{80}\text{Fe}_{20}$ film deposited on thin $(\text{Ni}_{80}\text{Fe}_{20})_{55}\text{Cr}_{44}$, $\text{Ni}_{52}\text{Cr}_{42}$ or Ta underlayer can be concluded to be due to resistivity reduction and $\Delta\rho$ increase by the increased grain size.

The results from BH measurements reveal that $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, $\text{Ni}_{58}\text{Cr}_{42}$ or Ta underlayer does not significantly change the magnetic properties of $\text{Ni}_{80}\text{Fe}_{20}$ film. There is no difference in the anisotropic field (H_k) and coercivity force (H_c) of $\text{Ni}_{80}\text{Fe}_{20}$ with or without underlayer. This experiment suggests that $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayers are the good candidates to enhance $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$.

Chapter 7

Conclusions

The electron transport and magnetic properties of $\text{Ni}_{80}\text{Fe}_{20}$, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, $\text{Ni}_{1-x}\text{Cr}_x$, $\text{Ni}_{80}\text{Fe}_{20}/(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$, $\text{Ni}_{80}\text{Fe}_{20}/\text{Ni}_{1-x}\text{Cr}_x$, and $\text{Ni}_{80}\text{Fe}_{20}/\text{Ta}$ thin films were studied in this thesis. $\text{Ni}_{1-x}\text{Cr}_x$ and $(\text{Ni}_{80}\text{Fe}_{20})_{1-x}\text{Cr}_x$ underlayer with the composition 44 and 42 wt% Cr, respectively, deposited by sputtering at room temperature caused significant enhancement of $\Delta\rho/\rho$ for $\text{Ni}_{80}\text{Fe}_{20}$. The $\Delta\rho/\rho$ enhancement was due to the decrease in resistivity and the increase in $\Delta\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$. These underlayers also induced strong (111) texture and large in-plane grain size of $\text{Ni}_{80}\text{Fe}_{20}$. The 45 Å $\text{Ni}_{58}\text{Cr}_{42}/\text{Ni}_{80}\text{Fe}_{20}$ and 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}/\text{Ni}_{80}\text{Fe}_{20}$ films produced the highest $\Delta\rho/\rho$ reported for $\text{Ni}_{80}\text{Fe}_{20}$. At 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ using 45 Å $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer, $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ is 3.60 % and 3.46 % respectively. The enhancement in $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ by the influence of these underlayers did not reduce the magnetic properties such as H_c and H_k of $\text{Ni}_{80}\text{Fe}_{20}$ film.

Table XI Results Summary.

	Best Underlayer		Permalloy			
	Cr wt%	Thickness (Å)	Thickness (Å)	$\Delta\rho/\rho$ (%)	ρ ($\mu\Omega\cdot\text{cm}$)	$\Delta\rho$ ($\mu\Omega\cdot\text{cm}$)
$(\text{Ni}_{80}\text{Fe}_{20})\text{Cr}$	44	45	~120	3.60	20.44	0.74
NiCr	42	45	~120	3.47	20.60	0.71
Ta	-	50	~120	2.5	27.0	0.61
$\text{Ni}_{80}\text{Fe}_{20}$	-	-	~123	1.76	33.20	0.58

The $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer thickness is an important parameter affecting the $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ thin film. The $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ thin films increases when the underlayer thickness increases from zero Å to 45 Å. Above 45 Å, $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ decreases from 45 Å to 80 Å. $\Delta\rho/\rho$ dependence on underlayer thickness was due to the induced (111) texture in $\text{Ni}_{80}\text{Fe}_{20}$ and electrical shunting in the underlayer.

The $\Delta\rho/\rho$ of $\text{Ni}_{80}\text{Fe}_{20}$ with and without underlayer increased with the $\text{Ni}_{80}\text{Fe}_{20}$ thickness. It is due to both decrease in ρ and increase in $\Delta\rho$. $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer are recommended to be used as a non-magnetic spacer.

$(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ and $\text{Ni}_{58}\text{Cr}_{42}$ underlayer enhance $\Delta\rho/\rho$ of permalloy film up to 94 % without changing the other magnetic properties such as coercivity (H_c) or anisotropic field (H_k) of permalloy.

The highest value of $\Delta\rho/\rho$ recorded in this study is 4.5 % for 340 Å $\text{Ni}_{80}\text{Fe}_{20}$, using a 45 Å $\text{Ni}_{58}\text{Cr}_{42}$ underlayer. $\Delta\rho/\rho$ of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$, MR thickness required for 1 GB read/write head, with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayers is 3.5%. ρ of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayers is 20.44 $\mu\Omega$ cm and 20.60 $\mu\Omega$ cm respectively. $\Delta\rho$ of 120 Å $\text{Ni}_{80}\text{Fe}_{20}$ with $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayers is 0.74 $\mu\Omega$ cm and 0.71 $\mu\Omega$ cm respectively. H_c and H_k of $\text{Ni}_{80}\text{Fe}_{20}$ remain approximately the same regardless of the $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ or $\text{Ni}_{58}\text{Cr}_{42}$ underlayers.

Appendix

A. Magnetron Sputtering: Film Deposition

IBM magnetron sputtering system number 136165c in room D3-253 is used for film deposition for the entire thesis. The sputtering chamber is shown in Figure 44. The actual sputtering system has four guns. Each gun has a different target mounted. The substrate holder is able to hold eight substrates per pump down. In the magnetron sputtering system, a magnetic field strength of 100-200 Gauss is used. The results are field lines, which confine the electrons to the region around the field. The discharge region is in a toroid or elongated ring, with extensive sputtering of the target. Substrates are placed on a rotating anode ring with the rotation around 30 rpm to obtain the uniformity of the deposited film. Four sets of circular cathode targets (2 inches in diameter) are placed on permanent magnets. The anodes and cathodes are located in a vacuum system in which inert gas, argon is filled. Radio frequency or DC is used to excite the glow discharge.

Figure 44. Magnetron sputtering chamber

Glow discharge is created by the breakdown of heavy inert gas such as argon. At sufficient electric field, the small current flows causing the electrons to transport between the cathodes (targets) and anodes (substrates). These electrons flow in the direction opposite to the electric field. Ar^+ , after ionized, accelerates through a potential gradient, and bombards through the targets. Because of the momentum transfer, atoms near the target surface become volatile and are transported as a vapor to the substrates. At the substrates, the film grows through deposition. The approximate film thickness is monitored inside the chamber during the deposition by using quartz crystal. The exact thickness is measured again outside the chamber by the use of profilometer. The thickness monitor is a resonance plate made from quartz crystal. Film thickness is measured by the acoustic impedance. The additional mass of the deposited film on the resonator that caused frequencies changes. The resonators have finite lifetime, since $\Delta f \propto \Delta M$ is true only for $0.05 \geq \Delta f / f_0$ (Δf = the resonator frequency change, ΔM = the additional deposit mass, f_0 = initial resonance frequency)^{37,38}. Figure 45 shows Ar^+ bombard cathode (target) resulting in sputtering.

Figure 45. The magnetron physical sputtering^{37, p 515}.

High argon gas flows around 5 m torr are used to continually sweep impurity out of the sputtering chamber. Operating pressures are approximately 3m torr. Base pressure of the sputtering system is in 1×10^{-7} torr range. Targets are presputtered at 30W for 8 minutes and at 200 W for another 8 minutes for target surfaces cleaning. Substrate position one is always uses as the dummy sample because this position is exposed to the presputtering period.

B. B/H loop: Magnetic Transport Measurement

The B/H Looper is an instrument often used in the analysis of soft magnetic materials. SHB 109 B-H Tracer is used for the transport magnetic measurement. Three types of measurements are performed with B/H looper: the easy axis magnetic measurement, the hard axis magnetic measurement, and $\Delta R/R$ measurement. The easy and hard axes are perpendicular to each other. Therefore, after the easy axis measurement is finished the sample must be rotated 90° away from the easy axis for the hard axis measurement. B/H looper gives details on how the magnetic material responds to a magnetic field in both hard and easy axes. The SHB 109 is shown in Figure 46. Two sets of long solenoid coils are used to create rapidly oscillating magnetic fields (H). The norm drive coils are the smaller coil (inner coils that perpendicular to the easy axis of the sample) around the pick up assembly. The larger, outer coils are the transverse drive coils. The oscilloscope is attached to the coils and the pick up assembly is used for presenting the hysteresis loop of the samples.

Figure 46. SHB 109 B-H Loop Tracer.

B-H loop for the easy axis and hard axis are the source for extracting important parameters such as remanance magnetization (B_r), Saturation magnetization (B_s), coercivity (H_c), and anisotropic field (H_k). An example of the hysteresis loop is shown in Figure 47.

Figure 47. B-H loop from 3 Å thick sample and 18mm diameter.

For B-H loop measurement, DC current flows through the Norm solenoids to create a Norm field ³⁹. The Norm fields are normally used for displaying hysteresis loops. The rapidly oscillating magnetic fields are mainly swiped and applied to the Norm axis. The sample flux (B) is picked up by the Norm pick up coils hidden in the pick up assembly. To measure B-H loop for an easy axis direction, the easy axis of the sample must be placed perpendicular to the Norm coils (as shown in Figure 48), and the easy axis must be rotated to the direction parallel to the Norm coils.

Figure 48. Norm coil and the direction of the sample easy axis.

For resistance and magnetoresistance ($\Delta R/R$) measurement, a sample is placed on the top part of the pick up assembly. This part functions as a four-point probe. For SHB 109, the probes are placed in the square pattern (2x1 rectangle). The standard in-line four-point probe is not suitable for saturation magnetoresistance measurement ¹⁰. This is because of its geometry. Magnetoresistivity is measured by evaluating resistance, $R_x(x, y)$, with a saturating magnetic field in X-direction, and $R_y(x, y)$ with the field in y-direction. The magnetoresistivity between x and y direction (easy and hard axis) is

$$Mr(x, y) \bullet \Delta \rho / \rho_0 = \Delta R / R_0 = (R_x - R_y) / 0.5 (R_x + R_y)$$

$M_r(x,y)$ is the probe factor which plotted in Figure 49.

Figure 49. Probe factor plot.¹⁰

The conventional in-line four-point probe that has the voltage probe at $y = 0$ has $M_r(x,0) = 0$ (from Figure 49). As the result, the conventional in-line four-point probe is insensitivity to magnetoresistivity.

Figure 50. The square probe geometry.

Square probe as shown in Figure 50 is the technique used for magnetoresistivity measurement. Since source current and sink current of the rectangle probe are at $(\pm 1,0)$

and voltage probes are at $(\pm 1, 1)$, $M_r(1, 1) = 0.993$ (this value is read out from Figure 50).

Therefore, the fractional resistance change using square probe is identical with the fundamental material magnetoresistivity ratio $(\Delta\rho/\rho_0)$. Figure 51 shows an example result from SHB 109 B-H Loop Tracer.

Figure 51 B/H loop of 150 Å permalloy.

C. Grazing Incident X-Ray Diffraction (GIXD)

Grazing Incidence X-ray Diffraction is the analytical tool for microstructure analysis of thin film, such as grain size, growth texture and interplanar spacing. This

The detector is moved along a diffraction circle, which is 20 inches in diameter, in the step of 0.15 degree with a counting time of 5 to 30 second at each step. Figure 53 shows an example of GIXD result with the diffraction planes identified.

Figure 53. GIXD of Pd deposited on Si.^{39,p 173}

Figure 54. The effect of crystal size on diffraction.^{36, p100}

The small crystals cause broadening (a small angle) of the diffraction beam. The diffraction is at angle near to (but not equal to) Bragg angle as shown in Figure 54 and 55. The angle θ_1 and θ_2 are deviated slightly from the exact Bragg angle (θ_B).

Figure 55. The effect of fine particle size on diffraction curve.^{40, p101}

The diffracted intensity at angle between $2\theta_1$ and $2\theta_2$, near $2\theta_B$, is not zero. The value is intermediate between 0 and the maximum intensity of the beam diffracted at Bragg angle ($2\theta_B$), and the value is shown in Figure 26(a). The hypothetical case of diffraction occurring at exact Bragg angle ($2\theta_B$) is shown in Figure 26 (b). The width of the diffraction curve increases as the thickness of the crystal increases because the angular range ($2\theta_1$ to $2\theta_2$) increases as “m” decreases,⁴⁰ which “m” is film thickness divided by interplanar spacing, $m = t/d$. The measurement of peak width at 2θ takes at half of the difference between two angles which their intensities are zero as shown in Figure 56. The assumption is that the diffraction line is triangular. Therefore,

$$B(2\theta) = 0.5 (2\theta_1 - 2\theta_2) = \theta_1 - \theta_2$$

Figure 56. The width $B(2\theta)$ are the angle in radians on 2θ scale at intensity full width at half maximum. ^{40, p 253}

When the difference between two angles (θ_1, θ_2) is zero ($\Delta Q = 0$), the center of the peak is at " $I_{\max}$ ", and $I(\Delta Q) = I_{\max}$

$$I(\Delta) = I_m \exp(-\pi(N \bullet a / \lambda)^2 (B/2)^2 (\cos\theta)^2)$$

When $I(\Delta) = I_{\max}/2$, the angle defined by Δ is the angle $B(2\theta)$ which is the angle at full width half maximum intensity.

$$1/2 = \exp(-\pi(N \bullet a / \lambda)^2 (B/2)^2 (\cos\theta)^2)$$

The value of $B(2\theta)$ is then given below

$$B(2\theta) = \{2 [(\ln 2) / \pi]^{1/2} \lambda\} / (N \bullet a \bullet \cos\theta)$$

$L = N \bullet a$ is the cube edge dimension of the crystal. " N " is the number of unit cells along the reciprocal direction. " a " is the reciprocal lattice.

D. Proton Induced X-Ray Emission: PIXE

PIXE technique provides a nondestructive analytical method of determining film composition. PIXE is based upon x-ray spectrometry or x-ray emission analysis. The elements present in the film are identified by the corresponding characteristic. PIXE is reliable, simple and fast.⁴¹ The sensitivity is up to parts per million ranges for most elements. An example of PIXE result is shown in Figure 57.

Figure 57. PIXE spectrum of 304 stainless steel.^{41, p 13}

A beam of protons is used to eject inner shell electrons from an atom in the film. When the outer-shell electrons fill the resulting vacancies, the characteristic x-rays are emitted. This energy identifies the particular atom. The transition filling vacancies in the innermost shells are called K x-rays, and those filling the outer shell are called L x-ray. Figure 29 shows the vacancy and the subsequent x-ray emission.

Figure 58. a) Proton bombardment ejects K-shell electron.

b) electron transition from outer shell causes x-ray to be emitted.^{41, p4}

The spectroscopy of the characteristic K and L x-rays emitted from a specimen is detected by using a lithium-drifted silicon detector. The high efficiency in x-rays energy regions of interest with a good resolution is typically 2 to 20 keV. For medium heavy elements, K x-rays are observed, and L x-rays are observed for heavy elements. Figure 59 shows how the atomic number relates to the x-rays emission energy of the elements.

Figure 59. The K and L x-rays energy correspond to their atomic number.^{41, p 13}

Figure 60. The arrangement of PIXE analysis.^{41.p5}

In Figure 60, the proton beam from an accelerator passes first through a bending magnet with a stable field. Passing through a slit then stabilizes the beam. After that, these energy analysis beams are directed axially down the beam line using electrostatic and magnetic steering element and enter the chamber. The detector and the Faraday cup are the most important for monitoring the proton current on the specimens. For the cost effectiveness of the accelerator and the quality of the information obtained, PIXE and Rutherford Backscattering are always used in combination. PIXE will be used to analyze only for monolayer films resulting from co-sputtering ($\text{Ni}_{58}\text{Cr}_{42}$, $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$, and $\text{Ni}_{80}\text{Cr}_{20}$). The studied film using PIXE are $\text{Ni}_{58}\text{Cr}_{42}$ and $(\text{Ni}_{80}\text{Fe}_{20})_{56}\text{Cr}_{44}$ 45 Å and $\text{Ni}_{80}\text{Cr}_{20}$ 45Å.

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