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Implementation of SEMPA Using a High Efficiency Retarding-Potential Mott Polarimeter

by

Julius Barnes, II

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree

Doctor of Philosophy

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ABSTRACT

Implementation of SEMPA Using a High Efficiency Retarding-Potential Mott Polarimeter

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Scanning Electron Microscopy with Polarization Analysis (SEMPA) provides a novel tool with which to image surface magnetic structure. In SEMPA, a tightly focussed electron beam is directed at the sample surface and the polarization of the ejected low-energy secondary electrons, which mirrors the local surface magnetization, is measured. A magnetic image is then built up by scanning the incident electron beam point-by-point over the sample surface. Here, a new SEMPA instrument is described that makes use of a high-efficiency retarding-potential Mott polarimeter. The incident electron beam is provided by an ISI-SX40 SEM column. Low-energy secondary electrons ejected from the sample surface are collected and transported to the Mott polarimeter by a series of electrostatic lenses. A Wein spin rotator is also included in the electron transport optics to allow
measurement of the full vector polarization of the ejected electrons, and thus the surface vector magnetization. Tests show that the performance of the present SEMPA instrument is superior to that of earlier designs. The apparatus has been used to image the domain structure on the surface of an Fe 3% Si sample, and to image tracks recorded in-plane on a cobalt alloy medium.
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Chapter 1

Introduction

A quantitative description of the magnetic microstructure of ferromagnetic thin films and solid systems is of interest for a number of technological applications. Domain dynamics has great impact on the performance and characteristics of hard magnetic materials in permanent magnets and is also important in the development of soft magnetic materials used to minimize losses in transformers and generators. Furthermore, an understanding of domain sizes and domain wall motion is essential to continue the development of thin film magnetic recording heads and media.

To obtain direct observation of the complex structure of magnetic domains, a number of magnetic imaging techniques have been developed. The Bitter method, like most methods used for magnetic imaging, makes use of the fringing fields from the ferromagnetic sample. Small magnetic particles are mixed in a solution and placed on the surface of the specimen. These cluster at the domain walls and their positions are imaged using a conventional optical microscope. In Lorentz microscopy, an incident electron beam is deflected by the residual magnetic field near the sample’s
surface. However this technique, like the Bitter method, does not offer high spatial resolution $^{2,3,4}$. One of the more recently developed techniques for magnetic imaging is magnetic force microscopy (MFM). MFM also makes use of the fringing fields from the sample surface. However, in this instance the contrast in the image is due to the magnetostatic interaction between the fringing fields and a magnetized probe tip. This technique offers easy access to the magnetic domain structure of the sample under investigation with relatively high spatial resolution ($< 50\text{nm}$) without any sample preparation $^5$. Due to these qualities, MFM is widely used and has become the industry standard. The magnetization of a sample can also be measured directly using the magneto-optical Kerr effect. In this approach, the rotation of the plane of the polarization of light after reflection from a magnetized surface is measured. Since this is an optical method, the spatial resolution of this technique is limited by diffraction $^6$.

Another magnetic imaging technique, scanning electron microscopy with polarization analysis (SEMPA) is the topic of this thesis. In SEMPA, a tightly focused electron beam is scanned across the surface of a ferromagnetic sample. The incident beam ejects low-energy secondary electrons which are collected from the sample surface and then transported to a spin analyzer via an electron lens system. Because the spin polarization
of the secondary electrons is antiparallel to the magnetization, measurements of the electron polarization as the incident beam is rastered over the surface can provide a two-dimensional magnetization map. This technique provides good magnetic contrast and is superior to Lorentz microscopy in two ways. First, the spin polarization of the secondary electrons is directly related to the magnetization vector which reveals both the magnetization magnitude and sign. Secondly, the magnetic image recorded with SEMPA is basically independent of the topography of the sample. In fact, both the magnetic and topographic images are measured simultaneously.

Initially, the concept of using spin polarized secondary electrons for magnetic imaging was suggested by DiStefano\textsuperscript{7} and Unguris et al.\textsuperscript{8}. The group at the National Institute of Standards and Technology (NIST) made the first measurements of the energy dependence of the spin polarization of the low energy secondary electrons. In these experiments, a 500 eV primary electron beam was directed onto an Fe-based ferromagnetic glass. The results showed a sizeable secondary electron spin polarization demonstrating the viability of SEMPA.

The first SEMPA instrument was built by Koike and Hayakawa. This apparatus consisted of a sample chamber, an electron gun with deflection
coils, a Mott detector, a signal processing unit and a cathode ray tube display. The electron gun used a tungsten hairpin filament and operated at an acceleration voltage of 10 kV, a probe current of 10nA, and a probe diameter of 10μm. Spin polarized electrons were collected and transferred to a Mott polarimeter where spin analysis was performed. For the first time, one component of the in-plane surface magnetization was measured. With this instrument, Koike and Hayakawa produced the first domain patterns on Fe(100) and Co(1210). They also demonstrated that the device had the capability of determining the magnetization direction, and it could also separate the topographic and magnetic data. The Mott detector used in this apparatus was of the conventional high-energy (100 keV) type and was both large and of relatively low efficiency$^9,10$.

Following this, Unguris et al. developed an improved SEMPA instrument which used an ultra-high-vacuum scanning electron microscope with a field emission source. The probe beam diameter was ~ 10nm with an incident current of ~ 3.0 pA. The best resolution achieved was ~ 50nm which was limited by the vibration of the sample stage. The spin analyzer employed was a low-energy diffuse scattering (LEDS) detector which operated at 150V and made use of an evaporated polycrystalline gold target. All three components of the magnetization vector were observed by using
two separate spin polarization analyzers. These low-energy detectors have poor electron optical acceptance and are very sensitive to the incident beam energy. Furthermore, the scattering is quite dependent on the state of the target surface and due to this the surface must be renewed periodically \(^{11}\).

In this thesis the implementation of SEMPA using a high-efficiency retarding-potential Mott polarimeter is demonstrated. First a description of ferromagnetism is presented. Following this, a detailed description of the apparatus is given along with some basic concepts. Next, the experimental procedures with some preliminary results are shown. Finally, future experiments are considered and the overall conclusions presented.
Chapter 2

Ferromagnetism

Since SEMPA will be used to image ferromagnetic domains, a brief discussion of ferromagnetism follows. First a discussion of the theoretical foundations of ferromagnetism is presented and following this some of the important experimental properties are summarized.

Ferromagnetism is due to the fact that electrons have spin and obey Pauli's exclusion principle. Even though ferromagnetism originates from relativistic effects, non-relativistic theory can account for some of the magnetic characteristics of ferromagnetism.

The full theory of ferromagnetism is based on relativistic electron dynamics and thus on Dirac's equation. Dirac's equation for an electron in an external electromagnetic field is

\[(E + mc^2)\psi = [-\alpha \cdot (c\bar{p} + e\bar{A}) - \beta mc^2 - e\phi]\psi.\]
\(\psi\) is a four component spinor, \(\alpha\) and \(\beta\) are the Dirac matrices. When the electrostatic potential is weak, i.e. \(e\Phi \ll mc^2\), the Dirac equation reduces to

\[
\left\{ \frac{\vec{p}^2}{2} - \phi + \frac{1}{2} \nabla \times \vec{A} \cdot \vec{\sigma} + \vec{A} \cdot \vec{p} + \frac{\alpha^2}{4} \left[ \nabla \phi \cdot \nabla - \frac{\vec{p}}{2} \cdot \vec{\sigma} \left( \nabla \phi \times \vec{p} \right) \right] \right\} \psi = E \psi
\]

which is Pauli's equation where \(\alpha\) is the fine structure constant. The first three terms are just Schrodinger's equation for an electron with spin, while the terms proportional to the square of the fine structure constant are the Darwin, mass-velocity, and spin-orbit corrections.

For the many-electron-case, there is no exact relativistic equation. However, accurate equations may be derived from quantum electrodynamics and by following arguments from Slater. In practice, a local density approximation (LDA) is made and calculations predicting the properties of ferromagnetic materials are based on the Kohn-Sham equation using the LDA. The relativistic Kohn-Sham equation for orbital \(i\) with eigenvalue \(\varepsilon_i\) is

\[
(\varepsilon_i + mc^2)\psi_i = \left[ -\check{\sigma} \cdot (c\vec{p} + e\vec{A}_{\text{eff}}) - e\vec{\sigma}' \cdot \vec{B}_{\text{eff}} - \beta mc^2 - e\Phi_{\text{eff}} \right] \psi_i.
\]

This equation has the same form as Dirac's equation except the term \(\vec{\sigma}' \cdot \vec{B}_{\text{eff}}\) has been added. \(\Phi_{\text{eff}}\) is the effective one-electron static potential and \(\vec{\sigma}'\) is the vector of diagonal Dirac spin matrices. \(\vec{A}_{\text{eff}}\) and \(\vec{B}_{\text{eff}}\) are the
effective vector potential and effective induction respectively. The effective quantities are expressed in terms of the classical equation with an additional term which depends on the local characteristics of the electron charge, current, and magnetization densities.

Like before, if \( e\varphi_{\text{eff}} \) is weak, the form of the equation reduces to the Pauli form and the Kohn-Sham equation becomes

\[
\left\{ \begin{array}{l}
\frac{\vec{p}^2}{2} - \varphi_{\text{eff}} + \frac{\vec{B}_{\text{eff}} \cdot \vec{\sigma}}{2} + \frac{\alpha^2}{4} \left[ \left( \nabla \varphi_{\text{eff}} \cdot \nabla - \frac{\vec{p}^2}{2} \right) \right] \\
- \frac{\alpha^2}{4} \left[ \vec{\sigma} \cdot (\nabla \varphi_{\text{eff}} \times \vec{p}) \right] \\
+ \frac{1}{2} \left( \nabla \times \vec{A}_{\text{eff}} \cdot \vec{\sigma} \right) + \left( \vec{A}_{\text{eff}} \cdot \vec{p} \right) \end{array} \right\} \psi_i = \varepsilon_i \psi_i .
\]

The first row constitutes what is termed the scalar-relativistic approximation in which ferromagnetism, i.e. a net magnetic moment, can be accounted for by the \( \vec{B}_{\text{eff}} \cdot \vec{\sigma} \) term. \( \vec{B}_{\text{eff}} \) is completely determined by the local spin-up and spin-down densities and is an exchange field which only couples to the electron spin. Here, the energy does not depend on the direction of spin quantization and thus there is no spin-orbit coupling and no magneto-crystalline anisotropy. The second row of the equation includes the spin-
orbit effects. When this term is included, the energy becomes a function of the spin quantization direction. Long range dipole-dipole interactions responsible for shape anisotropy and domain wall formation are accounted for by the last term. The full relativistic calculations can predict the magneto-crystalline anisotropy, the induced orbital moment, $<L>$ parallel to $<\mathbf{S}>$, and with this the gyromagnetic ratio.

The calculations reproduce the average spin moment quite well with errors below 1% for Fe $^{20-23}$. However, the values predicted for $<\mathbf{L}>$ frequently do not agree in sign and are in error by up to an order of magnitude $^{24-28}$.

Now that the theoretical foundations of ferromagnetism have been discussed, some of the experimental properties of ferromagnets are presented.

A ferromagnetic material is one in which below a critical temperature, the Curie temperature, spontaneous ordering of its magnetic moments can occur. In ferromagnetism, the moments are aligned parallel to each other.
In the absence of an applied magnetic field, soft magnetic materials do not possess a spontaneous net macroscopic magnetization. This is due to the fact that the ferromagnetic sample is not uniformly magnetized, but rather its volume is divided into uniformly magnetized microscopic regions termed magnetic domains, each of which is magnetized to saturation in different directions. The domain structure results from minimizing the free energy of the sample. The reduction of the magnetostatic energy associated with the flux leakage that occurs upon domain formation is shown in Figure 2.2. Domains are separated by boundaries known as domain walls in which the rotation of the magnetization direction occurs. Figure 2.3 displays the behavior of the spin magnetic moments in the vicinity of a 180 degree domain wall. When a ferromagnet is in the presence of an applied magnetic field, the magnetization is dependent upon the field magnitude and the direction in which it is applied relative to the crystallographic directions.
This property is known as the magneto-crystalline anisotropy and is due to spin-orbit effects.

The magnetization when external magnetic fields are applied in different crystallographic directions for iron are shown in Figure 2.4. The net sample
magnetization results from a combination of domain wall motion, domain vector rotation, and hysteresis. These processes are illustrated in Figure 2.5 which shows the changes in the domain structure and magnetization that occur as the applied field is increased. Figure 2.6 shows the corresponding hysteresis loop.

Figure 2.4 Magnetization as a function of the field for different crystallographic directions. (35)

Figure 2.5 Magnetization Process: Domain wall motion and finally domain vector rotation in the field direction. (35)
Figure 2.6 Portion of a hysteresis loop illustrating the remnant magnetization, coercivity, and magnetization saturation. (35)

Here a brief introduction to some of the salient features of ferromagnetism was presented.\textsuperscript{29-36}
Chapter 3

Experimental Apparatus and Basic Concepts

The implementation of SEMPA requires several basic elements: a SEM column, an electron collection system, an electron spin polarization analyzer, and a vacuum system with facilities for sample surface preparation and analysis. A description of each component of the SEMPA system follows.

3.1 SEM Column

The first component of the SEMPA system is the scanning electron microscope column that produces the tightly focused electron beam that impinges on the sample. The size of the final beam diameter determines the resolution of the image, and the amount of current controls the magnitude of the secondary electron signal. A typical SEM column is composed of an electron gun that provides a stable source of electrons and two multi-lens systems that control the beam current and final beam diameter. A description of the electron gun and the two multi-element lens systems is
presented. Following this, different aberrations that influence the image quality are discussed.

3.1.1 Electron Gun

The electron gun in the SEM column produces a stable source of electrons via thermionic emission in which the electrons in the heated cathode are thermally excited and escape the cathode. The type of cathode used in the electron gun greatly influences the beam properties and is usually a tungsten hairpin filament or a lanthanum hexaboride (LaB$_6$) crystal$^{37,38}$. Here a tungsten filament is used. During operation, electrons are emitted from the tip of the V-shaped filament and are accelerated toward the anode. The configuration of a typical electron gun is shown in Figure 3.1. A grid cap with a circular aperture is centered at the tip of the filament and is negatively biased relative to the cathode which repels the electrons and aids in focusing the electrons to a crossover dimension $d_0$ and divergence angle $\alpha_0$. 
The position of the grid cap relative to the filament tip is quite critical and also influences the electron focusing.

The current density, $J_B$, is the maximum intensity of electrons at the crossover and is defined as $J_B = \frac{4i_B}{\pi d_0^2}$ (A/cm²). Where, $i_B$ is the total emission current from the filament. The most important parameter for the electron gun is the brightness which is defined as $\beta = \frac{4i_B}{\pi d_0^2 \alpha_0^2}$ and the maximum brightness can be expressed as $\beta = \frac{J_C eE_0}{\pi kT}$ where $J_C$ is the
current density at the cathode, $E_0$ is the accelerating voltage, $e$ the electronic charge, and $k$ the Boltzmann constant. By using $J_B = \pi \beta \alpha_0^2$, the maximum current density may be expressed as $J_B = J_C \frac{e E_0 \alpha_0^2}{kT}$. The theoretical brightness can be approached by carefully choosing an optimum bias voltage between the grid cap and the cathode. The bias is produced by a variable bias resistor (see figure 3.1). The electron gun is also configured to produce a stable well-regulated beam current. By carefully setting the bias for maximum brightness, the beam current does not increase as the filament current is increased above a certain minimum value. This saturation condition occurs when the negative field gradient near the filament is increased to a value that limits the beam current$^{39}$.

3.1.2 Condenser and Objective Lenses

The column also contains two multi-lens systems. The condenser lens system controls the beam current at the sample, while the objective lens system, termed the final probe-forming lens, is responsible for final spot size of the beam. A typical SEM column, together with the SEMPA extraction optics, is shown in Figure 3.2.
To get a better picture of the inner workings of the lenses used in the condenser and objective lens systems, ray tracing through the lens systems is considered. In Figure 3.3 the trajectories of electrons as they pass from the crossover point through the lens systems are shown for a typical SEM column. The electron image at the cross over point is focused to a new dimension $d_i$ and divergence angle $\alpha_i$ after passing through the lens. By varying the strength of the condenser lens, the distance at which the
electrons are focused on the other side of the lens, $S_i$, can be adjusted. The demagnification of the lens is given by $M = \frac{S_0}{S_i}$ and the new diameter is related to the demagnification by $d_i = \frac{d_0}{M}$, where $M > 1$. Furthermore, the divergence angle $\alpha_i$ is related to the demagnification by $\alpha_i = \alpha_0 M$. Since the thickness of the lens is negligible, relative to lengths $S_i$ and $S_0$.

Figure 3.3 Ray traces in typical SEM column. (43)
and the Gaussian form of the thin lens equation from geometric optics is

\[ \frac{1}{S_0} + \frac{1}{S_i} = \frac{1}{f'} \]

valid which is given by \( \frac{I}{S_0} + \frac{I}{S_i} = \frac{I}{f'} \) \(^{38}\), where \( f' \) is the focal length of

the lens. If the objective lens is considered, the demagnification for this lens

is \( M_{obj} = \frac{S'}{S} \) and the final spot size is given by \( \frac{d_0}{MM_{obj}} \). The working
distance is defined as the distance from the bottom of the lowest pole piece
to the sample under investigation. The objective lens system can focus the
final beam spot over various working distances; however, when the working
distance is increased the demagnification decreases which generates a larger
final spot size. Thus shorter working distances favor small spot sizes and
better resolution. The current on the sample is also controlled by the
condenser/objective lens system. The amount of current that arrives at the
sample is the current at \( d_i \) times the ratio \( \frac{\alpha^2}{\alpha_i^2} \). Thus, by increasing \( M \) the
current at the sample is decreased \(^{40,41}\).

In the absence of aberrations, the current could be increased by
increasing the divergence angle at a constant beam diameter. However, due
to aberrations \( \alpha \) is constrained and this limits the current available for a
particular beam diameter.
3.1.3 Aberrations

There are four types of aberrations: spherical, chromatic, astigmatic, and aberrations due to diffraction. Spherical aberrations are due the fact that electrons experience a different value of the lens strength as they pass through the lens at different distances away from the optical axis. Further, the electrons that move on trajectories further away from the optical axis are focused more strongly than those that travel near the axis. This causes the image to be enlarged. The minimum size of the image is usually termed the disk of least confusion. For spherical aberrations, the diameter associated with this disk of least confusion is given by $d_s = \frac{1}{2} C_s \alpha^3$. $C_s$ is the spherical aberration coefficient which is a function of the beam energy and the focal length of the lens.

Chromatic aberrations are due to variations in the velocities of the electrons that pass through the lens. Thus electrons of different energies get focused to different points on the image plane. This process also causes the image to be enlarged and the diameter of the disk of least confusion for this aberration is expressed as $d_c = (\Delta E / E_0) C_c \alpha$. $\Delta E / E_0$ is the fractional
variation in the beam energy and $C_C$ is the chromatic aberration coefficient which is directly proportional to the focal length of the lens.

Due to the wave nature of electrons and the aperture size of the final lens, diffraction effects can cause aberrations. In this instance, the diameter of the disk of least confusion can be expressed as $d_d = 1.22\lambda/\alpha$. Errors in the magnetic lenses can produce asymmetric magnetic fields. Astigmatism, which is due to such errors, also causes an enlargement of the final beam size. However, a stigmator can be placed in the lens to supply a weak correcting magnetic field to produce the desired symmetry $^{38,42}$. To find the minimum final diameter at the maximum current the divergence angle must be optimized. The beam diameter is related to the various diameters of the disks of least confusion and the practical beam diameter $d_k$ by

$$d_p = \sqrt{\left(d_k^2 + d_C^2 + d_s^2 + d_d^2\right)}.$$ Each beam contribution of the overall diameter is regarded as an independent error quantity and these are added in quadrature. The optimum divergence angle is $\alpha_{opt} = \sqrt[3]{d/C_s}$. The minimum diameter is $d_{min} = 1.29C_s^{1/4}\lambda^{3/4} \left[7.92\left(\frac{iT}{J_C}\right)^{10^9} + 1\right]^{3/8}$ and the
maximum current is \( i_{\text{max}} = 1.26(J_C T^{2/3})\left[\frac{0.51d^{8/3}}{C_S^{2/3}\Lambda^2} - 1\right]10^{-10}. \) Here \( i_{\text{max}} \) is in amperes A, \( J_C \) in A/cm\(^2\) and \( T \) in kelvin K \(^{43,44}\).

In the present SEMPA apparatus, an ISI-SX40 scanning electron microscope column was used to produce the incident electron beam. A tungsten filament was used and the working distance was \( \sim 2.5 \) cm. The incident electron beam energy was 25-30 keV. The column was capable of producing currents of approximately 1 nA at a probe diameter of 400 nm and 0.30 nA at a probe diameter of 200 nm. A plot of the measured spot size as a function of the beam current is shown in Figure 3.4.

![Spot Size vs Beam Current](image)

**Figure 3.4** Plot of the spot size versus beam current for the present ISI-SX40 column.
The values for the current were measured using a Faraday cup and a picoammeter. The spot size was measured by sweeping the electron beam across a sharp edge located on a test sample and then measuring the change of the signal level as a function of the beam position. The line scan has the form shown in Figure 3.5. Typically, the value of the probe beam diameter is the distance from the 10% level to the 90% level.

![Figure 3.5 Electron signal when a Gaussian electron beam is swept across a sharp edge.](image)

### 3.2 Electron Beam Interactions

Another important consideration in SEMPA is the interaction of the incident electron beam with the atoms of the specimen via the electrostatic Coulomb potential. Incident electrons are scattered changing their momenta
and energies. In general, interactions may be classified as inelastic or elastic, respectively, depending on whether or not energy is lost in the process.

Furthermore, there exist an assortment of processes by which an electron beam of energy $E$ irradiating a solid surface may transfer energy and cause a secondary electron of energy $E'$ to be emitted from the surface. The typical energy distribution of the electrons ejected from a surface is shown in Figure 3.6 as a function of the energy $E'$.

![Figure 3.6 Typical energy spectrum of electrons ejected from a solid. (71)](image-url)
Near $E \sim E'$, there is a narrow peak, termed the quasi-elastic peak, which is composed of electrons scattered by phonons. This is followed by a low-intensity background comprising electrons that have experienced a number of inelastic interactions, including single and multiple electron-hole pair excitations. There are discrete peaks superimposed on the smooth background that are due to bulk and surface plasmon excitations and Auger processes which involve the excitation of core electrons. There is also a large broad low-energy peak that comprises true secondary electrons. These low-energy electrons are mainly conduction electrons excited by cascade processes in the solid. The origin of a feature in the distribution at some energy $E'$ can be classified by observing its behavior as the incident energy $E$ is varied. If $E'$ is related to $E$ by $w = E - E'$ or in multiples of $w$ then the process is due to inelastic scattering via excitations of energy $w$. However, if $E'$ is nearly independent of $E$ then the feature is due to secondary electrons emitted from the surface of the solid $^{45}$.

The spin polarization of inelastically scattered electrons produced by an unpolarized incident beam may be a consequence of spin dependences in the pertinent energy loss processes. The secondary electron cascade is due to inelastic scattering processes in which the following mechanisms make
some contribution: radiative de-excitation, electron-electron scattering involving electron-hole creation, plasmon excitation and decay, and electron-magnon interactions. The second of these processes is generally regarded as the source of the majority of the cascade of secondary electrons and is quite spin dependent.

The basic mechanism for electron-hole creation in a metal is electron-electron scattering due to the screened Coulomb interaction. Even though the interaction is intrinsically spin independent, Fermi statistics and the presence of exchange-split bands in ferromagnets can make spin quite important.

If we assume that the incident electron has spin \( \sigma_i \) and unit amplitude as an incoming wave in vacuum, and the target has spin \( \sigma_f \), the amplitude for the scattering event where the incident electron creates an electron-hole pair and then escapes and is detected may be denoted by

\[ f_{\sigma,\sigma'}(\eta, \varepsilon, q). \]

Here \( f \) represents direct scattering, and \( \eta \) is a set of quantum numbers that define the initial and final states of both electrons. \( f_{\uparrow \downarrow}(\eta, \varepsilon, q) \) and \( f_{\uparrow \uparrow}(\eta, \varepsilon, q) \) are generally not equal due to the fact that for exchange-split bands there will be different allowed states described by \( \eta \) for spin-up and spin-down electrons. However, if the target electron
escapes and is detected, the amplitude may be denoted by 
\[ g_{\sigma,\sigma'}(\eta, \epsilon, q) \] which indicates exchange scattering. For the case with 
\[ \sigma_i \neq \sigma_f \], the exchange event leads to a Stoner excitation in which the final 
state includes an electron and a hole of opposite spin. There are four 
scattering rates. Two are termed spin-flip where the scattered electron has 
participated in an exchange process that appears to generate a spin flip and 
the others are non-flip. Here the spin-flip rates are denoted by \( F \) and the 
non-flip rates are represented by \( N \). Furthermore, \( F_{\uparrow}(\epsilon, q) \) is the case 
where the incident electron has spin up and electron detected spin down. 
\[ F_{\downarrow}(\epsilon, q) \] is the case where the incident electron has spin down and electron 
detected spin up. \( N_{\downarrow}(\epsilon, q) \) is the case where the incident electron has spin 
down and electron detected has spin down. And \( N_{\uparrow}(\epsilon, q) \) is the case where 
the incident electron has spin up and the detected electron has spin up. In 
the absence of spin-orbit effects and multiple scattering, these partial 
intensities may be expressed in terms of the amplitudes by the following:

\[
N_{\uparrow}(\epsilon, q) = \sum \eta |f_{\uparrow\uparrow} - g_{\uparrow\uparrow}|^2 + |f_{\uparrow\downarrow}|^2
\]

\[
N_{\downarrow}(\epsilon, q) = \sum \eta |f_{\downarrow\downarrow} - g_{\downarrow\downarrow}|^2 + |f_{\downarrow\uparrow}|^2
\]
\[ F_{\downarrow}(\varepsilon, q) = \sum \eta |g_{\downarrow\uparrow}|^2 \]

\[ F_{\uparrow}(\varepsilon, q) = \sum \eta |g_{\uparrow\downarrow}|^2. \]

Here the sum over \( \eta \) is a sum over all electron states. This spans the allowed electron hole pairs of energy \( \varepsilon \), wave vector \( q \), and the required spin combination. The full information on flip and non-flip rates can be obtained only with a polarized incident beam and spin analysis. However, with an unpolarized beam and subsequent spin analysis with a polarization detector some valuable information can be gained. In this case, the polarization of the inelastically scattered electrons is expressed as

\[ P_{in}(E_p, \varepsilon, q) = \frac{N_{\uparrow} + F_{\downarrow} - (N_{\downarrow} + F_{\uparrow})}{N_{\uparrow} + F_{\downarrow} + N_{\downarrow} + F_{\uparrow}} \]

with \( E_p \) is the energy of the primary beam \(^{46}\).

### 3.3 Secondary Electrons

In 1902, Austin and Starke \(^{55}\) discovered that electron impact on a solid could lead to secondary electron emission. Following this in 1932, Fues and Hellman \(^{56}\) suggested that this might form the basis of a method for
extracting polarized electrons from a magnetized solid. The first experiments to measure the spin polarization of the secondary electrons were conducted in 1976 by Chrobok and Hofmann \(^{57}\). The sample used was EuO and spin polarizations as high as 32% were measured. A few years later Unguris et al. \(^{8}\) presented measurements of the energy dependence of the spin polarization of low-energy secondary electrons produced by a 500 eV primary beam incident on an iron-based ferromagnetic glass. The results are shown in Figure 3.7. The secondary electron spin polarization is a strong function of the energy. The polarization values are close to the known band polarization for electron energies above a few eV; however, larger polarization values are observed as the energy of the electrons decrease toward zero.

A number of explanations have been proposed for this enhancement of the polarization. One of these considers the polarization of the unfilled d-states in 3d ferromagnets. As the energy of an electron decreases, the probability that it will lose energy and fall into an unfilled state becomes larger. Since there are more minority-spin 3d holes, the minority-spin electrons are more likely to be removed from the electron distribution and scattered into these holes than the majority-spin electrons.
Figure 3.7 Plot of the polarization as a function of the energy. (8)

Thus, the net polarization is due to the difference of the spin dependent mean free paths.

The polarization measured is proportional to the net magnetization of the ferromagnet. For a ferromagnet, the spin part of the magnetization is $M = -\mu_B (n_\uparrow - n_\downarrow)$ where $n_\uparrow (n_\downarrow)$ are the number of spins per volume parallel (anti-parallel) to the quantization axis. Thus if low-energy secondary
electrons are excited from a ferromagnetic sample and transported to a spin analyzer, the magnetization can be measured. The SEMPA technique is illustrated in the Figure 3.8. Incident electrons from a conventional scanning electron microscope are directed onto the ferromagnetic sample ejecting low-energy secondary electrons. These electrons are collected from the sample surface of the and then transported to a spin polarization detector for analysis.

Another important parameter associated with secondary electron emission is the secondary electron ejection coefficient \( \delta \), defined as \( \delta = \frac{n_{SE}}{n_B} \) where \( n_{SE} \) is the number of secondary electrons emitted from the sample when bombarded by \( n_B \) incident electrons. A typical value for \( \delta \) is \( \sim 0.1 \) for an incident electron energy of 20 keV. However, under the appropriate conditions \( \delta \) can approach unity for samples such as MgO and Al₂O₃. \( \delta \) strongly depends on the beam energy. Starting from zero, the secondary electron ejection coefficient increases with increasing incident electron energy until reaching unity near 1 keV. Between 1-2 keV most metals display a broad peak with \( \delta \sim 1.0 \). Increasing the beam energy further, decreases the secondary electron ejection coefficient until \( \delta \) falls to
0.1 at energies of $\sim 20$ keV.

The secondary electron ejection coefficient is also a function of the angle of incidence $\theta$, the angle between the incident beam trajectory and the normal to the specimen surface. Experimentally, $\delta$ follows a secant law given by $\delta(\theta) = \delta_0 \sec \theta$. Where $\delta_0$ is the value of the electron ejection coefficient when the electrons are incident along the normal to the surface. For the present SEMPA operating conditions ($\theta \sim 65$, $E \sim 25-30$ keV) the secondary electron ejection coefficient is $\sim 0.2^{58,59}$.

True secondary electrons are usually defined as those electrons with energies below 50 eV. Low-energy electrons are strongly attenuated as they
traverse a specimen as a result of energy losses through strong inelastic scattering. Thus the sampling depth from which low-energy secondary electrons emerge is quite small. The maximum escape depth for most metals is only a few nanometers, although this increases to tens of nanometers for insulators.

3.4 Vacuum System

Since the sampling depth of the secondary electrons is quite small, the emitted electrons to be analyzed must originate from near the surface of the specimen. This makes SEMPA quite surface sensitive requiring the use of well-defined surfaces. To maintain a clean surface ultra-high vacuum (UHV) conditions are required. The time it takes for a single monolayer \(10^{15} \text{ atoms/cm}^2\) with atomic spacing 0.3nm of nitrogen atoms to form on a surface is related to the pressure \(p\) by \(t = 2.6 \times 10^{-6} / p\) in seconds. Here we assume that nitrogen is the only background gas and all the incident nitrogen molecules stick to the surface with unit probability \(^{60,61}\). At high pressures, surface contamination occurs very quickly. The presence of one or more adlayers drastically reduces the spin polarization of the ejected electrons and thus the magnetic contrast. To extend the monolayer
formation time to a reasonable value (> 1000 s) UHV is required, demanding use of a metal sealed bakeable vacuum chamber. To reach UHV conditions in a reasonable amount of time, the entire chamber is baked out which increases the rate of desorption of gases from the chamber walls. The bake out temperature was ~ 100\(^0\) C and was maintained for a few days. The vacuum system was equipped with a Phi Electronics model 20-115 ion sputtering gun which was used to sputter clean the surface of the samples. Argon ions produced in the ion gun impinge on the surface of the sample with an energy between 1-2 keV and knock off atoms that contaminate the surface. During sputtering the chamber was filled with high purity argon to a pressure of ~ \(10^{-5}\) Torr. The gun was equipped with focusing and scanning electrodes to optimize the current at the sample, and to raster the beam over the surface to clean larger areas.

3.5 Electron Optical System

The electrostatic lens system was designed to efficiently collect and transport the low-energy electrons to the spin analyzer and to minimize the instrumental asymmetries. A short description of the principles governing
the motion of electron beams is presented along with some technical details concerning the present electron optical system.

The motion of charged particles is controlled by the electromagnetic fields they traverse. Thus to control charged particles, one must first obtain an understanding of the nature of electromagnetic fields. The electromagnetic fields in vacuum are completely described by the vectors \( \vec{E}(\vec{r}, t) \) and \( \vec{B}(\vec{r}, t) \), while Maxwell’s equations express the relationship between these fields.

\[
\nabla \cdot \vec{E} = \rho / \varepsilon_0 \, , \, \nabla \cdot \vec{B} = 0 \, , \, \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \, , \, \nabla \times \vec{B} = \frac{\partial \vec{E}}{c^2 \partial t} + \mu_0 \vec{J} \quad \text{where } \rho
\]
is the charge density. Furthermore, a scalar potential \( \varphi \) and vector potential \( A \) may be introduced that satisfy the following equations:

\[
\vec{E} = -\nabla \varphi - \frac{\partial \vec{A}}{\partial t} \, , \, \vec{B} = \nabla \times \vec{A} \, . \quad \text{The force acting on a particle with charge } Q
\]
in the presence of an electromagnetic field is \( \vec{F} = Q(\vec{v} \times \vec{B} + \vec{E}) \). This force, termed the Lorentz force, is a function of both the electric field and the magnetic induction, and depends on the velocity of the charged particle. For the case where the fields are static, Maxwell’s equations are simplified yielding \( \nabla \times \vec{E} = 0 \) and \( \nabla \times \vec{B} = \mu_0 \vec{J} \). Under static conditions, the electric
field is determined by the scalar potential $\varphi$ alone, $E = -\nabla \varphi$, and this
leads to Poisson’s equation, $\nabla^2 \varphi = -\rho / \epsilon_0$. If $\rho = 0$, Poisson’s equation
reduces to Laplace’s equation, $\nabla^2 \varphi = 0$ \cite{65,66}.

In electron optics, one studies the motion of electron beams or other
charged particles as they traverse a series of electrostatic or magnetostatic
lenses. The trajectories of the individual electrons in the beam are also
determined. In a detailed theory of electron optics, the following properties
must be considered:

(1) particle nature of the electron

(2) the wave nature of the electron

(3) interactions with external fields

(4) radiative and short range space charge interactions.

In simple geometrical optics, the theory takes into account (1) and (3), but
neglects (2) and (4). This theory is expressed in terms of geometrical
concepts and since the fields are static, the electron spatial trajectories are of
great importance. Furthermore, the motion of charged particles is governed
by classical mechanics, thus the principle of least action, the variational
equation and Lagrangian dynamics form the basis for geometrical optics \cite{64}. 
In practice, the electrostatic fields used to control the electron beams are produced by a collection of electrodes held at suitable voltages. Magnetic fields, on the other hand, are provided by current carrying coils or permanent magnets. The coils, in most cases, are surrounded by ferromagnetic materials to localize the field and provide increased flux densities. The most commonly used electrode geometry is an axially symmetric series of electrostatic lenses.

The electrostatic lens system used in the present SEMPA apparatus consists of two main parts: a three-element einzel lens and a Wein spin rotator. The low-energy secondary electrons are collected from the surface of the grounded sample by the first element, a cone, and then enter a three-element einzel lens after traversing an entrance aperture. The middle element of the einzel lens system is divided into quadrants that can be biased independently. The application of small transverse voltage differentials provides beam steering allowing optimization of electron transport to the spin analyzer. The voltages used on the lens are shown in Figure 3.9.
Figure 3.9 A schematic diagram of the electron lens system.

The entire lens system was modelled and simulated using a computational package called SIMION. Electron trajectories for a particular set of operating conditions are shown in Figure 3.10. Use of such model calculations permitted the secondary electron collection efficiency to be determined as a function of the initial electron energy (see Figure 3.11).

Figure 3.10 Calculated electron trajectories through the present electron transport system
The present SEMPA apparatus is also equipped with a Wein spin rotator which is used to rotate the electron spin to allow measurement of all the components of the polarization. In general, a spin analyzer

![Graph: Electron Collection Efficiency](image)

**Figure 3.11** Calculated electron collection efficiency versus ejected electron energy for the present lens system.

only measures the two transverse components of the incident beam polarization. An end view of the rotator is shown in Figure 3.12.
The rotator produces mutually perpendicular electric and magnetic fields, both perpendicular to the electron trajectory. The fields are adjusted such that the electrostatic force cancels the Lorentz force, when the electrons are not deflected. This requires the magnitude of the electric and magnetic fields to be related by $E = \nu B$, the Wein condition. Although the electrons continue straight through the Wein filter, the electron spin polarization rotates about the magnetic field direction due to Larmor precession with frequency $\omega = \frac{eB}{m}$, where $e$ is the electronic charge and $m$ is the electron mass. After traversing a spin rotator of length $l$, the polarization has been rotated by an angle $\theta = \frac{elB}{mv}$. To determine the longitudinal component of
the polarization, the magnetic field is adjusted such that \( \theta = \frac{\pi}{2} \), while maintaining the Wein condition \(^{67,68}\). Since the net deflection of an entering electron depends on its velocity (and energy), the secondary electrons, which have an energy spread of a few electron volts, disperse spatially as they traverse the rotator and may not reach the analyzer. To minimize the relative energy spread and thus this dispersion, the low-energy electrons are accelerated to a pass energy of 2keV. With a pass energy of 2keV and a rotator length of .1m, a field of \( \sim 24 \) gauss is required for a 90 degree spin rotation. Following the Wein rotator, the electrons enter the Mott polarimeter for spin analysis.

3.6 Mott Polarimeter

There are a number of physical processes that are used to measure the electron spin polarization. However, most polarimeters take advantage of Mott scattering which makes use of the left-right scattering asymmetry that results from the spin-orbit interaction when electrons are scattered quasi-elastically at large angles from a high \( Z \) target. The origin of this effect can be understood by considering the interaction between the electron magnetic
moment and the magnetic field the electron experiences in its rest frame. In the rest frame of the electron, the charged nucleus moves. The current due to the moving charge gives rise to a magnetic field given by

\[ \vec{B} = -\frac{\vec{v} \times \vec{E}}{c} . \]

Figure 3.13 Magnetic and Electric fields experienced by a scattered electron.

The electric field of the nucleus is given by \( \vec{E} = \frac{Ze}{r^3} \vec{r} \) where \( \vec{r} \) is the separation between the nucleus and the electron. The magnetic field \( \vec{B} \) may be written in the form

\[ \vec{B} = \frac{Ze}{cr^3} \vec{r} \times \vec{v} . \]
This expression may be re-written as $\vec{B} = \frac{Ze}{mc^3} \vec{L}$. Here $\vec{L} = m \vec{r} \times \vec{v}$ is the electron orbital angular momentum. Figure 3.13 shows the magnetic and electric fields experienced by the scattered electron. The interaction between the electron magnetic moment $\vec{\mu}_S$ and the magnetic field gives rise to an additional term in the potential, the spin-orbit term $V_{SO} = -\vec{\mu}_S \cdot \vec{B}$. Since the electron spin magnetic moment and spin $S$ are related by

$$\vec{\mu}_S = \frac{g_S e}{2mc} \vec{S}$$

Figure 3.14 Potential plots with (dashed line) without (solid line) spin-orbit term.

the gyromagnetic ratio $g_S \approx 2$, the spin-orbit potential may be expressed as
\[ V_{SO} = \frac{Ze^2}{2m^2c^2r^3} \mathbf{L} \cdot \mathbf{S} \]. Here a factor of \( \frac{1}{2} \) has been included to account for Thomas precession. Figure 3.14 illustrates how the scattering potential will increase or decrease for spin-up or spin-down electrons depending on which side of the scattering center they pass. The spin-orbit term in the potential gives rise to a spin dependent differential scattering cross section which may be expressed as \( \sigma(\theta, \phi) = I(\theta)(1 + S(\theta)\mathbf{P} \cdot \mathbf{\hat{n}}) \). The spin-orbit interaction causes the cross section to increase (decrease) for electrons with spin parallel (anti-parallel) to the normal to the scattering plane. In the preceding expression, \( S(\theta) \) is the Sherman function, \( I(\theta) \) the angular distribution of scattered electrons, \( \mathbf{P} \) the electron polarization, and \( \mathbf{\hat{n}} \) the normal to the scattering plane, defined as \( \mathbf{\hat{n}} = \frac{\mathbf{k} \times \mathbf{k}'}{|\mathbf{k} \times \mathbf{k}'|} \) where the wave vectors of the incident and scattered electrons are represented by \( \mathbf{k} \) and \( \mathbf{k}' \), respectively. The Sherman function is a measure of the spin dependent scattering asymmetry and is a function of the beam energy and scattering angle. Note that only the component of the polarization vector perpendicular to the scattering plane contributes to the scattering asymmetry. For an unpolarized incident beam, the number of spin-up and spin-down electrons scattered into a particular direction is usually different yielding a
polarization \( \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \), which is proportional to \( \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \). The number of spin-up electrons scattered through an angle \( \theta_j \), is proportional to \( I + S(\theta_j) \), while the number of spin-down electrons scattered through the same angle, is proportional to \( I - S(\theta_j) \). The polarization after scattering is

\[
\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{I + S(\theta_j) - \{I - S(\theta_j)\}}{I + S(\theta_j) + \{I - S(\theta_j)\}} = S(\theta_j).
\]

If we now consider the scattering of the polarized beam with polarization \( P \), there will be an asymmetry in the number of electrons scattered to the left compared to the right which may be expressed as \( A(\theta_2) = \frac{N_L - N_R}{N_L + N_R} \). Using the fact that \( N_L \sim 1 + S(\theta_2)P \) and \( N_R \sim 1 - S(\theta_2)P \) one finds that \( A(\theta_2) = S(\theta_2)P \). Thus the left-right asymmetry is related to the incident beam polarization by the Sherman function. If one knows the value of the Sherman function and the asymmetry is measured, the polarization of the incident beam can be determined. Usually the Sherman function is replaced by an effective Sherman function, \( S_{\text{eff}} \), to account for multiple scattering in the target, and \( S_{\text{eff}} \) can be determined by measuring the asymmetry due to a beam of known polarization. The overall efficiency of a particular
polarimeter, termed the figure of merit, is expressed as \( F = \frac{I}{I_0} S_{\text{eff}}^2 \). Here \( I \) is the back-scattered current collected at the detectors and \( I_0 \) is the incident beam current. The best Mott polarimeters have figures of merit of \( \sim 10^{-4} \). Thus spin analyzers are quite inefficient and considerable effort has been devoted to improving the efficiency and reducing the size of such analyzers. The uncertainty in the measurement of the polarization \( P_0 \) of a sample of \( N_0 \) electrons is \( \delta P = \frac{1}{\sqrt{N_0 F}} \).^\text{71}

A number of Mott polarimeters have been developed for spin analysis that employ various mechanical designs and operating voltages. Here we review conventional and low-energy diffuse Mott polarimeters used by other groups in the implementation of SEMPA before describing the operation of our high-efficiency retarding potential polarimeter.

The pioneering group of Koike and Hayakawa used a conventional Mott polarimeter. A schematic of this device is shown in Figure 3.15. The secondary electrons are accelerated to 100 keV and
impinge upon a 100 μg/cm² gold target. The scattered electrons are then
detected by two surface barrier detectors positioned ±120° to the incident
beam. The efficiency of this polarimeter was \( \sim 10^{-6} \). This design is quite
large and requires accelerating column. the scattered electron detectors must
be biased at high potentials \(^{72}\).

More compact, yet efficient, spin analyzers have been developed. One
in particular, the low-energy diffuse scattering Mott polarimeter has been
used by the NIST group for SEMPA. A schematic diagram of the detector is shown in Figure 3.16. The input optics are used to focus

![Schematic diagram of LEDS polarimeter used by NIST group.](image)

Figure 3.16 Schematic diagram of LEDS polarimeter used by NIST group.

and accelerate incident electrons onto an evaporated polycrystalline amorphous gold target. A nearly field-free scattering region is produced by maintaining the target, drift tube, and electrode at the same potential. A positively biased grid G1, and negatively biased electrode E1 are used to deflect the scattered electrons. G2 is negatively biased to reject those electrons that have undergone inelastic energy losses. Electrons that are energetic enough to pass G2 are accelerated and detected. Once the
electrons pass through G2, they are then multiplied by the electron channel plates and are then detected by a four-quadrant high voltage anode. Low-energy diffuse scattering polarimeters can produce efficiencies that approach $2 \times 10^4$. However, the spread in the energy of the input beam must be minimized due to the energy sensitivity of low-energy Mott scattering. Also the high efficiency advantage is offset by the low electron optical acceptance of the detector. Typical values of this parameter for retarding-potential and conventional Mott polarimeters are $\sim 10^3 - 10^4 \text{ mm}^2 \text{ sr eV}$, while for low-energy diffuse scattering Mott polarimeters the value is $< 10^2 \text{ mm}^2 \text{ sr eV}$.

A schematic diagram of the Mott polarimeter used in the present SEMPA apparatus is shown in Figure 3.17. The electrons emerging from the Wein filter enter the Mott polarimeter. The electrons are scattered by a thorium target held at 25 kV. Electrons scattered at angles of $\pm 120^\circ$ pass through cone-shaped apertures in the inner assembly support. Next, the electrons enter retarding fields generated by a cylindrical focus electrode held at 1.5 kV and a circular retarding grid biased at 600 V. The circular grid is composed of copper photomesh (70 lines per inch, 90% optical transmission). The electrons are decelerated as they traverse the field and
only those electrons that have undergone small inelastic energy losses during scattering are able to surmount the retarding potential and be detected by the channeltrons. The inelastic energy loss window, $\Delta E$, is set by the voltage applied to the circular retarding grids and was typically $\sim 600$ eV.

Figure 3.17 Mott polarimeter used by our group including entrance optics.
These operating conditions produced an efficiency of $F \sim 1.6 \times 10^{-4}$ and an $S_{\text{eff}}$ of $\sim 0.2$.

### 3.7 Data Acquisition System

To determine the polarization, the count rates at all the channeltrons must be measured. The channeltrons were operated in the pulse counting mode. The output pulse from each channeltron is fed to a Lecroy TRA1000 preamplifier connected to a Lecroy 821 quad discriminator. After conversion from NIM to TTL voltage levels, the signals are counted by the PC-TIO-10 National Instruments I/O board installed in a Compaq Presario CDS 982 computer. A schematic diagram of the data acquisition system is shown in Figure 3.20.
Figure 3.20 A schematic diagram of data acquisition system.
Chapter 4

Results

During image acquisition, the count rates from the left, right, up, and down detectors are stored for each pixel. With these data, the transverse components of the polarization can be computed. The x- and y- components of the polarization, \( P_x \) and \( P_y \) are given by

\[
P_x = \frac{(N_u - N_d)}{S_{eff} (N_u + N_d)}
\]

and

\[
P_y = \frac{(N_L - N_R)}{S_{eff} (N_L + N_R)}
\]

respectively, where \( S_{eff} = 0.2 \). A topographic image of the surface can be obtained by the summing the count rates from all of the counters. Since the magnetization is anti-parallel to the ejected electron polarization, conversion of a polarization image to a magnetization image requires multiplication by -1. Furthermore, Mott polarimeters have an undetermined instrumental asymmetry that leads to an offset in the measured polarization. This offset can be measured by imaging areas containing several domains. The instrumental asymmetry can then be determined by assuming that the net magnetization of the imaged area is
zero. Once this correction is applied, the magnitude and direction of the magnetization vector can be analyzed.

Graphic representations of the magnetization maps can be formatted in two ways: first one may use two images showing separately the orthogonal magnetization components, i.e., $M_x$ and $M_y$. A color scale can be used to represent the range of values. Alternatively, one may show the magnitude and the direction of the magnetization vector. For most soft ferromagnets, the magnetization vector lies totally in-plane, and for this case the magnitude of the vector is $|M| = \sqrt{M_x^2 + M_y^2}$ and the direction of the magnetization vector relative to the positive x-axis is

$$\theta = \tan^{-1}\left(\frac{M_y}{M_x}\right).$$

Figure 4.1 shows the image of written tracks recorded in-plane on a cobalt alloy medium. The domains in the tracks with the one and two micron bit sizes are clearly resolved. Evidence of the transitions associated with a higher frequency track with a bit length of 0.3 microns is also visible. This sample was sputtered for ~ 3 hours with a 2.5 $\mu$A, 1keV argon ion beam to remove the carbon layer on the recording disc.

During image acquisition, the incident electron beam current was ~ 0.3nA and the dwell time was 250ms/pixel. The uncertainty was $\Delta P = \pm 0.012$
and the SNR = $2P / \Delta P$ was ~ 10. This result is comparable to that expected using the SEMPA apparatus of NIST which employs a high efficiency LEDS polarimeter for the same incident current and the dwelltime. A linescan of the image displaying the SNR is shown in Figure 4.2.

Figure 4.1 SEMPA image of tracks with two, one, and 0.3 micron bit lengths.
Figure 4.2 A line scan of the SEMPA image displaying SNR.

Figure 4.3 shows the domain structure at the surface of a Fe 3% Si sample. Both in-plane components of the surface magnetization were measured and the corresponding vector magnetization is indicated by arrows and color coding.
Figure 4.3 Vector magnetization image on Fe 3% Si sample. The image is ~ 60 microns square. The incident electron beam current was ~ 0.1nA and the dwell time was ~ 100ms/pixel.
Chapter 5

Future Work

The SEMPA apparatus discussed has enormous potential for use in additional investigations. One of the most intriguing groups of ferromagnetic materials is the series of amorphous alloys with the composition $T_{80}M_{20}$. Here T represents one or more transition metals Fe, Ni, Co, Mo, Cr, Mn, Pd, etc and M refers to one or more of the metalloid or glass-forming elements P, B, Si, or C. These alloys are quite interesting because of their potential applications.

Amorphous materials contain ions which are in non-periodic arrangements with the average distance between a pair of ions approaching that in a crystalline solid. However, the chemical structure is disordered. Gubanov predicted that ferromagnetism should be possible in amorphous materials. In crystalline ferromagnets, the exchange coupling is constant, while the exchange coupling in amorphous ferromagnets varies about the mean value of the inter-atomic spacing. Therefore, even though the amorphous material may have ferromagnetic properties, each magnetic moment may not be parallel.
Since the materials are amorphous, the physical properties should be isotropic. Thus these materials are not expected to have an overall magneto-crystalline anisotropy. However, due to magnetic interactions between nearest neighbor ion pairs and maybe next to nearest neighbors, which depend on ion separation and relative orientation, some type of local magneto-crystalline anisotropy is expected.

The domain structure of amorphous alloys is quite complex and may vary across the material. This is due to the cooling process inherent in the production of the alloy which generates residual stresses. The anisotropy may be in-plane or perpendicular to the plane of the material.

Amorphous ferromagnetic alloys have high potential for numerous applications. Perpendicular annealing can produce magnetomechanical coupling coefficients of ~ .95. This property has made $Fe_{81.5}B_{13}Si_{3.5}C_2$ attractive for elastomagnetic sensors. Other types of amorphous alloys may be used in transformers, recording heads, inductors, and erasable magneto-optical recording. Thus domain imaging of amorphous ferromagnetic alloys via SEMPA may be quite influential in the development of future technological applications.
Conclusions

In the present work, a SEMPA apparatus using a high efficiency retarding- potential Mott polarimeter was developed. This polarimeter provides an effective Sherman function of 0.2, under the appropriate operating conditions, and a figure of merit of $\sim 1.6 \times 10^{-4}$ which is comparable to other world class polarimeters. Magnetic images have been recorded and the instrument is suitable for a wide range of future studies which might include ferromagnetic amorphous alloys.
References


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