Scanning Electron Microscopy With Polarization Analysis (SEMPA)

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ABSTRACT

Scanning Electron Microscopy with Polarization Analysis (SEMPA) is a technique for the high spatial resolution imaging of magnetic microstructure. It employs a Scanning Electron Microscope (SEM) to create a finely focused electron beam on the surface of a ferromagnet; secondary electrons excited by the incident beam retain their spin-polarization when exiting the surface. A two dimensional map of the electron spin-polarization of these secondary electrons reveals the surface magnetization distribution for ferromagnetic (or ferrimagnetic) systems. This chapter describes salient features of the electron probe forming optics, the electron spin-polarization analyzers with associated transport optics, and the signal processing electronics. We also give examples illustrating how SEMPA provides high resolution magnetization images of various classes of micromagnetic structure.

1.1 INTRODUCTION

Scanning Electron Microscopy with Polarization Analysis (SEMPA)[1] is a technique that provides high resolution images of magnetic microstructure by measuring the spin polarization of low energy secondary electrons generated in a scanning electron microscope [2-5]. This is possible because the emitted secondary electrons retain the spin polarization present in the material; SEMPA therefore produces a direct image of the direction and magnitude of the magnetization in the region probed by the incident SEM electron beam. SEMPA determines all three components of the spin polarization, and hence of the magnetization. SEMPA records the magnetic and topographic images simultaneously, but independently. Polarization is normalized to the number of emitted electrons, i.e. to the intensity, or the quantity measured in a secondary electron SEM topographic image. Thus, SEMPA measurements are intrinsically independent of topography. This feature allows the investigation of the correlation between magnetic and topographic structures. SEMPA can characterize ferromagnetic materials with a sensitivity down to a fraction of an atomic layer and a lateral resolution of 20 nm. The surface sensitivity of SEMPA is particularly advantageous for studies of thin film and surface magnetism[6,7] but puts requirements on the cleanliness of specimen surfaces. SEMPA also enjoys other advantages common to scanning electron microscopes, such as long working distance, large depth of field, and large range of magnifications. The zoom capability is especially useful for imaging the magnetization distribution in ferromagnets where length scales vary over several orders of magnitude from relatively large (>10 μm) magnetic structures such as ferromagnet domains, to intermediate size

(200 nm) structures found in Bloch, Néel, asymmetric Bloch or cross-tie domain walls, to the finest structures (<50 nm) found in magnetic singularities such as Bloch lines, Néel caps and magnetic swirls.

To put SEMPA in perspective, it is useful to compare it to other methods of imaging magnetic microstructure, some of which are discussed at length in other chapters of this handbook. Different magnetic imaging methods are distinguished by the quantity measured to obtain magnetic contrast, the resolution, the ease of interpretation of the measurement, the requirements on sample thickness and surface preparation, the cost, and so on. A summary of this information for the various imaging techniques mentioned below is displayed in Table I. The values given for the resolution of each technique are estimates of the current state of the art; they should only be taken as a rough guide.

Most methods used for the observation of magnetic microstructure rely on the magnetic fields in and around a ferromagnet to produce magnetic contrast. For example, the oldest method for imaging magnetic microstructure is the Bitter method [8] where fine magnetic particles in solution are placed on the surface of a ferromagnet. The particles agglomerate in the fringe fields at domain walls thereby delineating the magnetic domains; the particles may be observed in an optical microscope or even an SEM. In Lorentz microscopy, the magnetic contrast is derived from the deflection of a focused electron probe as it traverses a ferromagnetic sample [9,10]. In the transmission electron microscope (TEM), Lorentz microscopy can achieve a high lateral resolution of order 10 nm, but the measurement represents an average over specimen

thickness. Only thin samples (< 300 nm) are suitable for high spatial resolution studies. Unfortunately, such thin samples may not have a magnetization distribution characteristic of the bulk. Lorentz microscopy in the reflection mode in an SEM has also been demonstrated[11]. It has the advantage that the near surface of bulk specimens can be examined, but the lateral resolution is seldom much better than 1 μm. Electron holography [12,13] is an electron interferometric method for obtaining absolute values of the magnetic flux in and around thin ferromagnetic samples. It is a high resolution (2 nm) method with contrast derived from the measurement of electron phase shifts that occur in electromagnetic fields. Differential phase contrast microscopy also measures electron phase shifts to give magnetic contrast at high lateral resolution (2 nm) in the scanning TEM [14]. Magnetic force microscopy (MFM) is an imaging technique suitable for thick (bulk) specimens. It achieves contrast through the magnetostatic interaction between a ferromagnetic tip and the fringe fields of the ferromagnet. MFM can be used to locate domain walls with a spatial resolution of about 10 nm, but it is difficult to extract quantitative information from MFM images [15].

Direct methods for measuring micromagnetic structure rely on contrast mechanisms which reveal the magnetization rather than the magnetic induction. The magneto-optic Kerr effect [16] uses the rotation of the plane of polarization of light upon reflection to map surface magnetization distributions. As an optical method, its spatial resolution is diffraction limited to optical wavelengths, but it has the advantage that a magnetic field can be applied and varied during measurement. Magnetic circular dichroism (MCD) images domains using a photoelectron microscope [17]. Photoelectron

images are recorded for circularly polarized incident x-rays. Since the photoelectron yield is proportional to the spin-dependent density of states at the surface and the helicity of the x-rays which selectively excite atomic core levels, images of domain structure can be obtained with elemental specificity. Although the information depth within the magnetic material is about 2 nm, secondaries from a 10 nm carbon overcoat have been found to reflect the underlying magnetic structure [17]. Spin-polarized low energy electron microscopy (SPLEEM) is a very new high resolution (20 nm) method for resolving surface magnetic microstructure [18] which relies on the spin-dependence of the (quasi)elastic scattering cross section for polarized electrons from ferromagnets. A spin polarized electron source is required to modulate the spin of the incident beam. Magneto-optic Kerr, MCD, and SPLEEM are like SEMPA in that they measure quantities directly proportional to the sample magnetization.

1.2 PRINCIPLE OF SEMPA

Scanning Electron Microscopy with Polarization Analysis (SEMPA), first demonstrated in the mid 1980's[19-23], is a micromagnetic imaging technique that derives magnetic contrast from the spin polarization of secondary electrons extracted from a ferromagnetic surface. The secondary electron magnetic moments are parallel, and consequently their spins antiparallel, to the magnetization vector at their point of origin in the sample [24].

The SEMPA method is schematically depicted in Fig. 1. As the electron beam is scanned across the sample, the secondary electrons are collected and their polarization

analyzed. An electron spin analyzer measures each component of the polarization vector, $\underline{P}$, separately. For example the x-component of polarization is given by

$$P_x = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) \quad (1)$$

where $N_\uparrow$ ($N_\downarrow$) are the number of electrons detected with spins parallel (antiparallel) to the +x direction. The degree of electron spin-polarization varies in the range $-1 \leq P \leq 1$. Note that P is a normalized to the total number of electrons emitted, $(N_\uparrow + N_\downarrow)$. The polarization and intensity are measured simultaneously, but independently. Thus, the magnetic and topographic images are determined separately.

Spin polarized secondary electrons emitted from a ferromagnet reflect the spin part of the magnetization,

$$M = -\mu_B(n_\uparrow - n_\downarrow). \quad (2)$$

Here $n_\uparrow$ ($n_\downarrow$) are the number of spins per unit volume parallel (antiparallel) to a particular orientation, and μ_B is the Bohr magneton. To the extent that the secondary electron cascade represents a uniform excitation of the valence electrons, the expected secondary electron polarization can be estimated as $P = n_B/n_{v,}$ where n_B is the number of Bohr magnetons per atom and n_v the number of valence electrons per atom. In this way, one estimates a polarization of 0.28, 0.19, and 0.05 for Fe, Co and Ni respectively, These agree reasonably well with measurements of secondary electrons in the 10 to 20 eV range.[25,26]. At lower energies, spin dependent scattering [27] actually increases the polarization, improving the contrast in SEMPA measurements. SEMPA provides vector magnetization maps for conducting or semiconducting bulk specimens, and thin films and monolayer films where specimen charging is not a problem. In some cases

charging can be avoided and the magnetization enhanced by evaporating a 1 nm thick film of Fe on the specimen; this has allowed the imaging of insulating Fe garnets [28]. The magnetization along the measurement direction is proportional, but oppositely directed, to the electron polarization along that direction. In practice, the constant of proportionality is not precisely known; the detailed scattering dynamics for the production of polarized secondary electrons is dependent upon the surface band structure, which varies from material to material. Measurements using SEMPA reveal the spatial dependence of the relative value of the surface magnetization distribution rather than the absolute size of the surface moments.

Important features of SEMPA include its high spatial resolution and its surface sensitivity. The spatial resolution of SEMPA is primarily determined by the incident beam diameter focused on the sample surface. Even though the profile of the energy deposited in bulk samples expands greatly in the bulk due to multiple scattering [11], the escape depth of polarized secondary electrons is on the order of nanometers. The 1/e sampling depth, or attenuation length for spin-polarized secondary electrons, is about 0.5 nm for a transition metal like Cr [29], and about 1.5 nm for a noble metal like Ag [30]. Although SEMPA measures only the near-surface micromagnetic structure, the underlying and bulk magnetic structure can be determined by solution of the micromagnetic equations using the surface magnetization measurements as boundary conditions [31]. The surface sensitivity of SEMPA is advantageous for studies of surface and thin film magnetism but can be a limitation in the sense that sample surfaces must be clean. Thick oxides or hydrocarbon layers will diminish the polarization and hence the

magnetic contrast.

1.3 INSTRUMENTATION

The electron probe forming column, transport optics, and spin-polarization detectors comprise the essential electron optical components of the SEMPA system. A schematic of a SEMPA instrument is shown in figure 2. Because of the surface sensitivity of SEMPA, the specimen should be cleaned and maintained in ultrahigh vacuum ($P < 5 \times 10^{-8}$ Pa). Conventional surface science preparation and analysis tools including an ion-beam sputtering gun, an electron beam evaporator, an Auger electron spectrometer and a reflection high energy electron diffraction screen greatly facilitate the preparation and characterization of the sample surface. The SEMPA system may be equipped with a single spin detector [4-7], or multiple spin detectors [2,3] as shown in figure 2. Two detectors are used for the acquisition of all three orthogonal components of the vector polarization (magnetization) signal. The SEM probe forming column, the transport optics, the polarization analyzers, the electronics and signal processing will be considered in turn. A general description will be given of the generic components of SEMPA; we will use our apparatus as an example for detailed analysis.

1.3.1 SEM Probe Forming Column

An SEM beam of 10 keV is a reasonable compromise among the constraints of secondary electron yield, spatial resolution, and beam stability in the secondary electron extraction field. The beam energy must be high enough to reduce the deleterious effects of electron lens aberrations, yet low enough to sustain reasonable secondary

electron yields from the sample. Submicrometer beam diameters can be obtained for electron energies above 5 keV while the secondary electron yield, for example from Al, falls from 0.40 at an incident beam energy of 5 keV to 0.05 at 50 keV [11]. The incident electron beam must also be energetic enough such that the extraction optics which transport the polarized secondary electrons to the spin detector do not severely aberrate the focused spot on the sample. Extraction optics typically have fields on the order of 100 V/mm to achieve adequate collection efficiency. A 10 keV beam suffers minimal distortion in such an extraction field.

Two essential components of the electron optical column, the electron source and the probe forming objective lens, can be optimized for SEMPA. For reasonable SEMPA acquisition times, electron sources must provide a 10 keV incident beam with a current of at least 1 nA to the specimen. It is this constraint that determines the SEMPA spatial resolution rather than the ultimate resolution of the column when used as a standard SEM. The selection of an electron source rests on the spatial resolution required for a specific micromagnetic measurement. Lanthanum hexaboride (LaB_6) [2,3], cold field emission cathodes [4-7], and thermal field emitters[32] have all been employed in SEMPA. The highest resolution, approximately 20 nm, has been achieved with field emitters. Thermal field emitters [33,34] have somewhat larger source size than cold field emitters, but have greater stability (current variations < 1%), high emission currents, and moderate energy width, making them well suited for use in high resolution SEMPA systems.

In SEM columns, the spherical aberration of the probe forming objective lens

increases rapidly with increasing working distance, the distance between the lens exit pole face and the sample. For high resolution, one wants a short working distance. On the other hand, longer working distances are desirable to obtain a region at the sample surface free (< 1 Oe) from the depolarizing effects of the stray magnetic field of the objective lens. Working distances between 5 and 15 mm provide a satisfactory trade off.

1.3.2 Transport Optics

The purpose of the transport optics is to efficiently collect and transfer the spin-polarized secondary electrons from the specimen surface to the spin-polarization detectors without introducing instrumental asymmetries. Instrumental asymmetries are systematic errors which may be accounted for in a variety of ways. To reduce the effects of chromatic aberrations on the transported beam, the secondary electrons are first accelerated in a potential greater than about 500 V. In order to achieve the highest possible efficiency, the transport energy window of the electron optics should be about 8 eV wide and centered at 4 eV. The optical properties of low energy electron lenses used for transport can be computed from the numerical solution of Laplace's equation and subsequent ray tracing of the charged particle trajectories through the fields. An invaluable compendium of electron optical properties of common electron lens configurations has been compiled by Harting and Read [35]. At low magnification, the motion of the incident SEM beam on the specimen is translated into motion of the beam on the spin analyzer target leading to an instrumental asymmetry; a dynamic beam descanning scheme can be employed to remove scan related asymmetries [3]. The transport optics can be further optimized to reduce instrumental asymmetries and

compensate for variations in the position of the beam [36].

1.3.3 Electron Spin Polarization Analyzers

Ideally a spin-polarimeter suitable for SEMPA should be efficient, small in size and compatible with the UHV ambient required for sample preparation. There has been considerable progress in reducing the size and increasing the efficiency of electron spin-polarimeters, yet spin detectors remain quite inefficient [37]. The polarization of a beam of N_o electrons is $P_o \pm \delta P$, where the uncertainty is $\delta P = 1/(N_o F)^{1/2}$. The figure of merit, F, for a spin polarization analyzer, rarely is much greater than 10^{-4} even for the highest performance spin detectors. Thus, a polarization measurement with a relative uncertainty, $\delta P/P_o = 1/(P_o^2 N_o F)^{1/2}$, equivalent to the relative uncertainty in an intensity measurement, $\delta N/N_o = 1/(N_o)^{1/2}$, can take over 10^4 times as long as the intensity measurement solely due to the inefficiency of the electron polarimeter.

Most spin polarimeters rely on a spin-orbit interaction for spin sensitivity. When an electron scatters from a central potential $V(\underline{r})$, the interaction of the electron spin $\underline{s}$ with its own orbital angular momentum $\underline{L}$ [38] has the effect of making the cross section larger or smaller for electrons with spin parallel or anti-parallel to $\underline{n}$, the unit vector normal to the scattering plane. The scattering plane is defined by the incident electron wave-vector $\underline{k}_i$ and scattered electron wave-vector $\underline{k}_f$ such that $\underline{n} = (\underline{k}_i \times \underline{k}_f)/|\underline{k}_i \times \underline{k}_f|$. The cross section for the spin-dependent scattering can be written [38] as

$$\sigma(\Theta) = I(\Theta) [1 + S(\Theta) \underline{P} \bullet \underline{n}] \qquad (3)$$

where $I(\Theta)$ is the angular distribution of back scattered current in the detector and $S(\Theta)$ is the Sherman function for the detector scattering material at the scattering angle, Θ.

The Sherman function is a measure of the strength of the spin-dependent scattering in the detector [39]. Typical values for S are $|S| < 0.3$. The polarization of the beam is determined from a spatial asymmetry A between the number of electrons scattered to the left, N_L, and to the right, N_R, relative to the incident beam direction. The measured scattering asymmetry, A, is

$$A = (N_L - N_R)/(N_L + N_R) = PS \quad (4)$$

Differences in the left/right scattering can also arise from instrumental asymmetries and cause systematic errors that contribute to the uncertainty in the polarization measurement. These instrumental asymmetries result from; (1) unequal gains in the left and right channels of the signal processing electronics; (2) unequal sensitivities of the electron multipliers; and (3) mechanical imperfections which result in a detector geometry that is not symmetric.

As an example of a scattering type spin analyzer, we describe the low energy diffuse scattering (LEDS) detector [36,40] used in our work. A schematic of this analyzer is shown in Fig. 3. The analyzer is quite compact since it operates at 150 eV; in our design it is about 10 cm long. It employs an evaporated polycrystalline Au target. The efficiency of this spin analyzer is increased by collecting the scattered electrons over large solid angles. The large ratio of electrons collected to the number incident compensates for the moderate Sherman function of about 0.1, and leads to a high figure of merit, 2×10^{-4} [36]. The electrodes E1 and E2 in Fig. 3 focus the electrons that are diffusely back-scattered from the Au target such that their trajectories are nearly normal to the retarding grids G1 and G2. The energy selectivity of the retarding grids enhances

the Sherman function while the collection efficiency is increased by electrodes E1 and E2. The anode, which is also shown in the inset of Fig. 3, is divided into quadrants. Two orthogonal components of the polarization vector transverse to the electron beam direction (z) may be measured simultaneously with this detector as

$$P_x = 1/S\ (N_C - N_A)/(N_C + N_A) \quad (5a)$$

$$P_y = 1/S\ (N_B - N_D)/(N_B + N_D) \quad (5b)$$

where N_i is the number of electrons counted by each quadrant.

No single electron spin analyzer has all the features one might desire for highest performance in a SEMPA application. The traditional Mott analyzer which utilizes the asymmetry of the spin-dependent high energy (100-200 keV) electrons [38,41,42] has a Sherman function S that is larger than that of the LEDS detector and a comparable figure of merit. The high energy operation makes it less susceptible to apparatus asymmetries than low energy spin analyzers which therefore require more care in design of the transport optics. However, operation at the required high voltage leads to large detector sizes making the Mott analyzer challenging to integrate with the SEM. Nevertheless, such analyzers have been used quite successfully for SEMPA[4,7]. A low energy electron diffraction (LEED) electron-spin polarization analyzer[43,44] has also been used very successfully for SEMPA[5,6]. The collimating properties of diffraction by a single crystal, usually W(100) at about 100 eV, increase the efficiency of this spin analyzer leading to a relatively compact analyzer with a competitive figure of merit.

1.3.4 Electronics and Signal Processing

The electron signal is measured with surface barrier Si detectors, channeltrons, or

stacked microchannel plates with a segmented anode, respectively, in the Mott, LEED, and LEDS spin analyzers. Each pair of detectors determines a component of the spin polarization vector transverse to the beam. For pulse counting, each signal channel consists of a preamplifier, amplifier/discriminator, and a scaler that is read by the computer. The signal processing electronics for the LEDS spin analyzer have been realized in both the pulse counting and analog modes; we describe aspects of each of these methods below.

When the electron probe beam is focused to very high spatial resolution in the SEM column, the beam current is reduced and pulse counting in the polarimeter is necessary. The short pulse widths (about 1 ns) in stacked microchannel plates facilitate high speed counting. Dark currents are typically less than 1 count/cm^2/sec. In pulse counting, the quadrant anode structure must be designed to minimize cross talk between adjacent channels. Otherwise, pulses from adjacent channels will appear at reduced amplitude making pulse discrimination difficult. Reduction of inter-anode capacitance and capacitive coupling from each anode to common surrounding surfaces is effective in reducing this problem. Fast (20 ns) charge sensitive preamps can also be used. These are less affected by crosstalk than voltage preamps because they average over the characteristic ringing signal of capacitively coupled cross talk.

Fast, low resolution magnetization imaging with high incident current is very useful to survey a sample. At high incident beam currents, analog signal processing becomes necessary since the microchannel plates are count rate limited [45,46]. With separate direct-coupled outputs from the anode quadrants, it is straightforward to switch over to

an analog measurement of the current to the quadrants. When analog detection is used at high incident beam currents, the channel plate bias voltage is decreased to maintain linear gain. Each anode pair is connected to signal processing electronics including matched current-to-voltage converters, and sum and difference amplifiers. (Alternatively, the sum and difference can be performed later in the computer). The sum and difference signals are converted to pulse trains by separate voltage to frequency converters. Opto-couplers provide the isolation necessary for the input stages to operate at the microchannel plate anode voltage and the signals are counted with a conventional scaler and timer system. Since the difference signal may change sign, an offset voltage is applied to that voltage-to-frequency converter to prevent zero crossing and minimize digitization errors [3].

1.4 SYSTEM PERFORMANCE

The performance of a SEMPA system can be analyzed by examining the efficiency of the entire production, collection and processing chain. Although some of the considerations in the analysis are generally applicable to any SEMPA system, in order to provide specific numbers we will give parameters for our SEMPA system with the LEDS spin analyzer [2,3]. The production efficiency of secondary electrons by a 10 keV electron beam at the surface of a ferromagnetic specimen tilted by 45^{o}, is roughly 0.45 [11]. Only 37 % of the secondary electrons produced at the sample are collected since the extraction optics only collect a narrow secondary electron energy window, 4.0 eV ± 4.0 eV. The efficiency of the transport optics between the extraction aperture and

the spin analyzer may be as high as 1.00, but for normal operation the transport efficiency is closer to 0.88. The scattering efficiency, or ratio of the current incident on the detector channel plate input to that incident on the Au target, is 0.04 for nominal operating conditions[36,40]. The channel plate itself has a finite collection efficiency of about 0.85 [46] due to final cell size. The product of all of these factors is the collection efficiency of the system, ϵ=0.005. For 1 nA incident beam current, only 4 pA (.004 I_o) of secondary electrons will be detected in the electron polarimeter, or approximately 1 pA to each quadrant.

Signal levels and integration times required to reach selected signal-to-noise ratios can also be estimated [3]. The simplest case to consider is the image of two adjacent domains with oppositely directed magnetization. Assume that the sample is oriented along a single detector direction such that the measured component of the polarization will be +P in one domain and -P in the other. The total change in that polarization component between the two domains, i.e. the signal, is 2P. For a polarization measurement limited by counting statistics[38], one standard deviation statistical error in the polarization, $P=(1/S)(N_C-N_A)/(N_C+N_A)$, is given by $\delta P=(1/(N_C+N_A)S^2)^{1/2}$. The particle number reaching any pair of detector quadrants (N_A+N_C) in a time interval τ is $\epsilon(I_o/2e)\tau$. The signal-to-noise ratio is

$$SNR \equiv 2P/\delta P = 2PS(\epsilon I_o \tau/2e)^{1/2}. \quad (6)$$

The dwell time required for each pixel in the image as a function of the desired signal-to-noise ratio and the experimental parameters is

$$\tau = (SNR)^2 e/(2P^2S^2\epsilon I_o). \quad (7)$$

The upper limit on the count rate will be set by the channel plate response. Assuming that the incident electron beam current in the electron microscope column is I_o=1 nA and S=0.11, the dwell time per pixel for various signal-to-noise ratios, and polarizations is given in Table 2. The elements in the table must be multiplied by the number of pixels in an image for the total data acquisition time. Thus, it takes about 54 seconds to acquire a 256 x 256 pixel image with a signal to noise ratio of 5 and a mean polarization of 0.20. For analog signal detection, it is possible to reduce the noise introduced by the analog amplifier well below the shot noise of the incident beam for incident currents $\geq$1 nA. Hence the dwell times given in Table 2 also apply for analog signal acquisition.

1.5 DATA PROCESSING

Conventional image processing methods, such as filtering and contrast enhancement, can be used for processing SEMPA images. There are however, some image processing steps that are unique to SEMPA since the contrast is derived from a vector magnetization and the spin detector sensitivity results from a scattering asymmetry. For SEMPA, common image processing steps include the subtraction of a zero offset and a background asymmetry. To do this, use is made of the fact that the magnitude of the magnetization |M| is constant. Consider the common case where the magnetization vector lies entirely in-plane. (This is expected for all but materials with particularly large magnetic anisotropy perpendicular to the surface.) In this case, it is possible to subtract a background and remove zero offsets by requiring that the in plane

magnetization, $(M_x^2 + M_y^2)^{1/2}$, have constant magnitude. In general, the background subtracted may be non-linear and fit with a polynomial. In special cases, the specimen topography can cause trajectories which couple with instrumental asymmetries to produce artifacts in the polarization measurements. In such cases the polarization detector's Au target can be replaced by a low atomic number target, such as graphite, for which there is no spin-dependent scattering asymmetry. The image acquired with the graphite target is then subtracted from that acquired with the Au target to remove instrumental asymmetries.

There are two basic formats to represent SEMPA data. The first uses the projection of the magnetization on orthogonal axes, i.e. M_x and M_y, and uses a gray map encoding scheme where white (black) represents the maximum value of the magnetization in the positive (negative) directions. The second format uses the magnitude |M| and the angle ϑ of the magnetization vector projected onto some plane. Whether it is easier to identify a surface magnetic domain structure in M_x and M_y images or in |M| and ϑ images depends largely upon the surface magnetic microstructure. The magnitude of the magnetization is determined as,

$$|M| = [\, M_x^2 + M_y^2 + M_z^2 \,]^{1/2} \qquad (8)$$

and the direction with respect to the positive x-axis of the in-plane magnetization is (in the absence of any out-of-plane components)

$$\vartheta = \tan^{-1} (M_y/M_x). \qquad (9)$$

The map of the angle ϑ can be displayed using color where the direction is read from an accompanying color wheel. Alternatively, it is sometimes helpful to visualize the

magnetization pattern by using small arrows to create a vector map.

1.6 EXAMPLES

1.6.1 Iron Single Crystals

The large magnetic moment per atom of Fe leads to a large intrinsic secondary electron polarization which makes Fe a favorable specimen to use for demonstrating SEMPA features. Figure 4 shows SEMPA images [2] of the (100) surface of a high quality Fe single crystal whisker. In the image labeled I, one observes the flat featureless upper surface of the whisker running vertically, centered in the frame. The image of the x-component of the magnetization, M_x , shows a diamond-shaped domain with magnetization pointing to the right. The domain pattern is shown schematically in the line drawing. The region to the right of the diamond in the figure is the non-magnetic sample holder; to the left is the side of the crystal. The image of the vertical component of the magnetization, M_y , contains domains with magnetization pointing in the +y direction (white) and in the -y direction (black). The zig-zag domain wall visible in this image actually runs down the side of the whisker and is visible because the sample is slightly tilted. This large depth of focus is characteristic of SEMPA since a scanning electron microscope is used as the probe.

1.6.2 CoPt Magneto-optic Recording Media

In magneto-optic recording, information is stored by using a focused laser beam to read and write the bits. A bit is written when the laser locally heats the media in an applied magnetic field. The result is seen in Fig. 5 where the white dots correspond to

magnetization out of plane, M_z, in the +z direction contrasted against a background previously magnetized in the -z direction. The corresponding intensity image shows the nonuniform topography of the Co-Pt multilayer sample. In use, the bits are read by sensing the rotation of polarization of reflected light from the surface. The circular bits observed in Fig. 5 are about 1.4 micrometer diameter. A large perpendicular magnetic anisotropy is necessary to overcome the increased magnetostatic energy of out-of-plane magnetization. Domains with out-of-plane magnetization have also been observed on Co(0001) single crystals[47] and on TbFeCo magneto-optic storage media[48].

1.6.3 Exchange Coupling of Magnetic Layers

Two ferromagnetic layers separated by a nonferromagnetic layer may be exchange coupled such that the magnetic moments in the two ferromagnetic layers are parallel (ferromagnetic exchange coupling) or antiparallel (antiferromagnetic exchange coupling) depending on the spacer layer material and its thickness. An example is two Fe layers separated by a Cr layer to form a sandwich structure Fe/Cr/Fe(100). SEMPA is particularly well suited to determine the period (or periods) of oscillation of the exchange coupling between the magnetic layers as a function of spacer layer thickness [49,50]. For example, consider the Fe/Cr/Fe(100) sandwich structure shown schematically in Fig. 6. A varying thickness Cr "wedge" is deposited on the Fe(100) whisker substrate. This is covered with an Fe film approximately 10 layers thick. As shown in the schematic, the Fe layers are ferromagnetically coupled for small Cr thickness, and the sign of the coupling oscillates as the Cr thickness increases.

The SEMPA image of the magnetization in the direction of the wedge shows

many changes in the magnetization as the Cr increases in thickness to nearly 80 layers (1 layer = 0.14 nm) over the length of the wedge shown in the image, about 0.8 mm. Such an image allows a very precise determination of the period of the exchange coupling. At Cr thicknesses where there is a reversal in the magnetic coupling, one observes a component of the magnetization transverse to the wedge direction as seen in the upper magnetization image. This provided early evidence for a different kind of coupling known as biquadratic exchange coupling.

Several features of SEMPA were successfully exploited in these studies. The high spatial resolution of the SEM allows the use of a small, nearly perfect Fe single crystal whisker substrate. The ultrahigh vacuum allows deposition of a Cr wedge in situ. The clear advantage of the wedge structure is that it allows measurements at many different thicknesses with a reproducibility that could not be obtained by producing multiple films of uniform thickness. With a reflection high energy diffraction (RHEED) screen below the sample stage, and using the SEM column as a RHEED gun, it is possible to make spatially resolved RHEED measurements along the Cr wedge to determine the thickness of the interlayer material with single atomic layer resolution. The surface sensitivity of SEMPA allows the observation of the changes in the magnetization direction of the Fe overlayer without any interference from the lower Fe layer. Finally, since the SEMPA system used for these measurements was part of a scanning Auger microprobe, Auger spectroscopy could be utilized to monitor cleanliness of the specimen at each stage of its preparation.

1.6.4 Magnetic Singularities in Fe-SiO_2 Films

A high resolution field emission SEMPA was used to image magnetic singularities in granular Fe-SiO_2 films above the percolation threshold [51]. These are nanocomposite materials with highly isotropic magnetic properties [52]. Fig. 7 shows a segment of a 180° domain wall with two cross ties and a dramatic ripple pattern. Fig. 7(a) depicts the x-component of the magnetization. This image clearly shows the fine structure of the ripple pattern; the cross ties appear as diamond shaped regions elongated in the direction orthogonal to the wall. In the y-component image, Fig. 7(b), the wall itself is readily apparent. The vector map representation given in Fig. 7(c) shows the coarse structure of the ripple and the vortices that occur between cross ties.

Because SEMPA is only sensitive to the magnetization at the surface, it is ideally suited to an investigation of surface features such as the singularities in Fig. 7. Line scans taken across the large central vortex indicate that the in-plane component of the magnetization decreases within the vortex showing that there must be a perpendicular component of the magnetization. The resolution of these images was determined to be 20 nm by analysis of line scans across several surface features.

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Figure Captions

Fig. 1: The principal of SEMPA. A scanned beam of electrons incident on the surface of a ferromagnet creates spin-polarized secondary electrons which are subsequently spin-analyzed to yield a high resolution magnetization image.

Fig. 2: Schematic of a SEMPA apparatus. The electron source, polarization detectors, cylindrical mirror analyzer (CMA), and reflection high energy electron diffraction (RHEED) screen are shown in their actual relative positions; the rest of the instruments are not. The CMA and polarization analyzers are retractable.

Fig. 3: Schematic of the low energy diffuse scattering spin polarization analyzer. The divided anode assembly is shown in the inset as viewed from the Au target.

Fig. 4: SEMPA measurements of the topography, I, and images of two components of the magnetization, M_x and M_y, from an Fe whisker. The depth of focus is demonstrated by domains clearly visible on the top and side of this slightly tilted sample of rectangular cross section.

Fig. 5: The topography, I, and perpendicular magnetization, M_z, are imaged from a CoPt magneto-optic recording media. The round bits are approximately 1.4 micrometer in diameter.

Fig. 6: The magnetization images, M_x and M_y, of the top layer of a Fe/Cr/Fe(100) sandwich structure, shown schematically at the bottom, provide a precise measure of the oscillation of the sign of the magnetic exchange coupling as the thickness of the Cr spacer layer increases.

Fig. 7: SEMPA images of the in-plane magnetization in a Fe-SiO_2 fillm near a domain wall: (a) x-component image; (b) y-component image; (c) vector map representation.

Table 1: Comparison of Several Magnetic Imaging Techniques

Method	Quantity measured	Resolution (nm)	Information depth (nm)	Reference
SEMPA	magnetization	20	1	2-7
Magneto-optic Kerr	magnetization	500	10	16
MCD	magnetization	300	2	17
SPLEEM	magnetization	20	1	18
Bitter	field	1000	1000	8
MFM	field	10	1000	15
TEM Lorentz	field	2	average through sample	9,10
STEM Differential Phase Contrast	field	2		14
Electron holography	field	2		12,13

Table 2: Pixel dwell time, τ (msec), as a function of the SNR and polarization for SEM beam current, I_o = 1 nA

P	SNR = 2	SNR = 3	SNR = 5	SNR = 10
0.01	53.185	119.666	332.407	1329.626
0.10	0.532	1.197	3.324	13.296
0.20	0.133	0.299	0.831	3.324
0.40	0.033	0.075	0.208	0.831