SCANNING ELECTRON MICROSCOPY WITH POLARIZATION ANALYSIS (SEMPA): HIGH SPATIAL RESOLUTION MAGNETIC IMAGING STATUS REPORT

M.R. Scheinfein, J. Unguris, D.T. Pierce and R.J. Celotta
National Bureau of Standards, Gaithersburg, MD 20899

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The scanning electron microscopy with polarization analysis (SEMPA) technique as a means of observing magnetic microsctructure is surveyed. A brief description of the technique is given. Particular emphasis is paid to the spin-polarization detector as the critical element in the SEMPA system.

1 Introduction

Secondary electrons emitted from a ferromagnetic target irradiated by fast electrons retain the spin polarization related to the net spin density of the valence electrons [1]. Spin polarization analysis of these emitted secondary electrons is thus a direct probe of the magnitude and direction of the local magnetization. When spin polarization analysis is coupled with a scanning beam instrument such as a high resolution scanning electron microscope (SEM), magnetic microstructure information may be extracted [2,3,4]. The polarization information is independent of the topographic contrast or Z contrast of the sample being probed. Further, the spin polarization images may be acquired while secondary and backscatter images are simultaneously acquired. This makes scanning electron microscopy with polarization analysis (SEMPA) a powerful technique for studying magnetic microstructure.

Efforts to probe magnetic microstructure have existed since early in this century. The oldest and simplest method for observing magnetic microstructure is the Bitter technique [5] where fine magnetic particles are attracted to

domain boundaries by the magnetic fields emanating from domain structures in the observed specimen. These patterns are usually seen under an optical microscope. Magneto-optic effects for the observation of domain structures, the Faraday effect [6] in optical transmission, and the Kerr effect [7] in optical reflection rely on the fact that the polarization vector of polarized light rotates by interaction with magnetic samples. The polarization vector rotation is directly related to the magnetization. Transmission electron microscope images of magnetic microstructure may be obtained by Lorentz microscopy [8]. Here, the magnetic microstructure can be imaged by the deflection of the defocussed electron beam as it passes through the magnetic field of the domain structures. Electron holography [9] and differential phase contrast microscopy [10] also image magnetic microstructure in the transmission electron microscope. For all of the electron transmission techniques, the specimen must be sufficiently thin, which may introduce limitations in the systems which can be observed. Finally, a new technique, the atomic force microscope (AFM) [11], is capable of resolving magnetic fringing fields by measuring the deflection force in an intrument very much related to the conventional scanning tunneling microscope (STM).

In the SEMPA technique, a highly focused beam of electrons is scanned across a sample surface creating secondary electrons. The spin polarization of the secondary electrons is analyzed pixel by pixel as the beam is scanned. The advantages of this technique are [12]: 1) high spatial resolution is possible with a suitable probe forming instrument such as a high resolution SEM as the resolution is expected to be the same as that in a secondary electron intensity image; 2) the polarization signal is directly proportional to the sample magnetization; and 3) the contrast should be high and independent of the secondary electron intensity contrast. Koike et al. [13] were the first group to acquire SEMPA images using a 10 micron diameter, scanned, focused electron beam and a conventional high voltage Mott detector as the spin analyzer. Subsequent work by Koike et al. [13,14,15,16] demostrated increased resolution and improved magnetic contrast. The main difference between Koike's efforts and those at NBS involve the choice of instrumentation, primarily the spin-polarization analyzer. Recently, other groups at IBM, MIT, KFA, Sussex, and Carnegie Mellon have begun SEMPA programs.

2 The SEMPA Technique

In the SEMPA technique, a SEM focuses and scans electrons on a magnetic sample, which may, for example, have some magnetic domain structure where the magnetization (direction) may change over small distances, such as seen in a domain wall structure. The secondary electrons that are generated by the main beam are collected and their polarization is measured. As the magnetization is a vector quantity, three independent measurements of the beam polarization are necessary to quantify the specimen magnetization. Since the polarized

electrons are extremely sensitive to non-magnetic surface layers, conventional surface science vacuum and cleaning techniques must be employed. A detailed review of the complete SEMPA instrumentation and data acquisition can be found in reference 4. Here, we will emphasize the spin-polarization detector and some recent improvements implemented in the NBS diffuse electron scattering detector.

3 Spin Polarization Detectors

The polarization of a beam relative to some quantization axis is the ensemble average of the expectation value of the Pauli spin operator. The statistical description of a mixture of spin states of a polarized beam is thus appropriately described in the density matrix formalism. The polarization P can be conveniently expressed as

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \tag{1}$$

where $N_\uparrow$ and $N_\downarrow$ are the number of electrons with spins parallel and antiparallel to the quantization axis. The degree of polarization has the range $-1 \leq P \leq 1$. In the spin polarization detector, a mechanism for separating the spins is provided, usually utilizing the left/right asymmetry resulting from the spin orbit coupling in high angle collisions with heavy atoms.

The high energy (conventional) Mott analyzer [17] has been widely used to measure electron spin polarization. This analyzer utilizes the scattering asymmetry resulting from high energy (100 keV) electrons scattering from heavy amorphous metal (usually Au) films. The degree which the analyzer is able to separate the beam polarization is characterized by its Sherman function S. The Sherman function is a measure of the scattering asymmetry in the detector integrated over the collection solid angles. In a typical Mott detector, the scattered electrons are detected by two apertures located 30 degrees above the Au film and oriented opposite each other, eg. at azimuth angles of 0 and 180 degrees respectively. Mott detectors have typical Sherman functions of $S = 0.25$. The figure of merit for a polarimeter is defined as [18]

$$FOM = \frac{S^2 I}{I_o} \tag{2}$$

where S is the Sherman function, I is the current detected by the two opposite detectors and I_o is the incident beam current. A Typical FOM for the Mott detector can be as high as $1 \, x \, 10^{-4}$. The figure of merit is related to the signal to noise parameter of the detector. Due to the inherent difficulty in separating the spins, polarized electron spectroscopy has lagged other electron spectroscopies.

Improvements to the traditional Mott analyzer have been made whereby beam energies have been reduced to 20 - 30 keV [19,20]. These detectors have

Sherman functions of approximately 0.13 and a *FOM* of 2 x 10^{-5}. When the target is a single crystal instead of an amorphous or polycrystalline film, the left/right asymmetry due to spin-orbit scattering is present in the diffracted beams, and a detector based on this principle has been developed [21].

The low energy diffuse scattering polarization detector [22] is used in the SEMPA system at NBS. This detector, developed at NBS, also relies on the spin-orbit interaction of low energy electrons (150 eV) with an amorphous Au target to produce a left/right asymmetry. A schematic of this analyzer is shown in figure 1. A beam of unknown polarization at an energy of 150 eV is incident on the evaporated Au target. Electrons are scattered from the Au and detected by the quadrants A-D. The polarization in the x-direction is determined by

$$P_x = \frac{(N_C - N_A)}{(N_C + N_A)S} \tag{3}$$

where N_i is the number of electrons detected by quadrant i and S is the Sherman function for the detector. Similarly, the polarization in the y-direction is determined by

$$P_y = \frac{(N_B - N_D)}{(N_B + N_D)S} \tag{4}$$

To determine the polarization in the z-direction, the beam of electrons is electrostatically deflected by 90 degrees to another detector. In the electrostatic deflection, the polarization is unchanged, and the z-component, which was normal and is now transverse, can easily be measured.

The Sherman function of this detector is 0.11 and the *FOM* can be as large as 2.3 x 10^{-4} due to the large solid angles collected by the quadrants. All of the polarimeters discussed are position sensitive detectors. The detectors are position sensitive in the sense that motion of the beam at the Au film will cause an asymmetry to be measured. This asymmetry is a false or instrumental asymmetry and needs to be eliminated or controlled.

One method of controlling the false asymmetry of this detector is to account for the following trends which will be discussed only qualitatively here. If the beam moves towards quadrant B along the x-axis of figure 1, and it is still normal to the Au film, then more electrons will be detected in quadrant B due to the larger solid angle and the fact that the cross- section is higher as the backscatter angle in increased. If the beam intersects the film at the symmetry axis, but is tilted towards quadrant D, then quadrant D will detect more electrons due to the increased cross- section in the backscattered direction. Thus, if the beam moves and we can focus it onto the detector with the correct amount of displacement and tilt, the asymmetry due to displacements can exactly cancel out the asymmetry due to tilts, and beam motion at the object point can be eliminated from producing any false asymmetry at the detector. This technique is being developed for our detectors and we have compensated the beam movement asymmetry. Measurements indicate that the asymmetry

is less than 0.003/mm of beam movement at the specimen, which means that, for a SEMPA experiment where the scan may be over a 100 micron sample, an uncertainty in the polarization of less than 0.3 % results.

4 Conclusion

The success of the SEMPA technique lies largely in the proper implementation of the polarization detectors. Detailed electron optical design is necessary to insure that the magnetic contrast mechanisms will not be degraded by spurious effects. Further work will determine the ultimate spatial resolution of the technique as more magnetic systems are explored with more sophisticated instrumentation.

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