Polarized Light Emission from the Metal-Metal STM Junction

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Abstract

The polarization of light emitted during inelastic tunneling of electrons into both Au(111) and Fe(001) using W(111) tips in an STM junction has been fully characterized by measuring the Stokes parameters. The emitted light for both Au(111) and Fe(001) is fully polarized; it is predominantly linearly polarized in the plane formed by the tip axis and direction of light emission. For both samples, there is a small circular polarization which is tip dependent and can be attributed to tip asymmetries. No magnetization dependent circular polarization was observed for Fe(001).

PACS: 61.16.Ch, 78.60.Fi, 75.30.Pd

Introduction

Measurable macroscopic magnetic properties are controlled by microscopic properties for which there are insufficient direct measurement techniques. Technological advances leading to higher density magnetic information storage and smaller magnetic devices are driving magnetic measurement requirements further towards nanometer resolution. The development of a general method of adding magnetic contrast to scanning tunneling microscopy is a widely recognized challenge that would not only allow high spatial resolution magnetic imaging, but would also allow correlation of magnetic microstructure with topographic and spectroscopic properties measured by the STM [1].

A few years ago, the phenomenon of light emission from a metal-metal STM junction was investigated. The picture that has evolved [2,3] is that electromagnetic modes of the coupled tip-sample system are excited by inelastic electron tunneling as shown in Fig. 1. The resulting dipolar radiation is expected to be linearly polarized in a plane defined by the direction of the tunneling current and the emitted light.

Recently, it was reported that STM-stimulated luminescence emitted from a tunnel junction that included a ferromagnetic material had an unexpected circularly polarized component the sign of which was related to the direction of magnetization [4,5]. Preliminary measurements on a polycrystalline Ni surface found circular polarization exceeding 50% that was sensitive to the surface topography [4]. Subsequent measurements showed that large circular polarization could be measured even on nonmagnetic samples when tip asymmetries were present [6]. Nevertheless, measurements on a Co(0001) thin film grown on Au(111) found a change in circular polarization of order 10% when the magnetization of the film was reversed [5]. This effect has been treated theoretically. [7,8]

The promise of this intriguing result for magnetic imaging on the nanometer scale led us to make further measurements of this type. Our goals were 1) to test the generality of this effect by measuring a different ferromagnetic material, 2) to eliminate surface roughness as a possible source of change in circular polarization, and 3) to fully characterize the polarization of the tunneling-induced luminescence to try to understand the underlying mechanism. To accomplish the first two of these goals we use an Fe(001) whisker which we have shown with RHEED and STM to be a high quality single crystal that has a very flat surface with terrace widths of approximately 1 micrometer [9]. The polarization was fully characterized by measuring the Stokes parameters of the STM-stimulated radiation. We describe briefly the method to determine the Stokes parameters, the experimental setup, and finally present a discussion of the results for Au(111) and Fe(001).

Experimental Details

The experiments were performed in an ultra-high-vacuum system with capabilities for room-temperature STM, sample and tip preparation, and reflection high energy electron diffraction, as previously described [9]. The STM measurements were made with single crystal (111)-oriented W tips. The tips were cleaned by field evaporation during which the sharpness and cleanliness were monitored by field electron emission. The Fe whiskers were cleaned by sputtering at 750 °C with Ne.

To characterize the polarization of the light emitted from the STM junction, the light is passed through a rotating quarter wave plate and a fixed linear analyzer as shown in Fig.2 (a). This is one of the simplest of the ellipsometric designs that has been used for a direct measurement of all four Stokes parameters [10]. The intensity of the light reaching the detector as the quarter wave plate is rotated through an angle Θ can be written as,

$$I(\Theta) = [A + B\sin(2\Theta) + C\cos(4\Theta) + D\sin(4\Theta)]\ /2. \qquad (1)$$

The coefficients A, B, C, and D are related to the Stokes parameters which are defined in the usual way [11,12],

$$S_0 = E_x E_x^* + E_y E_y^* = A - C \qquad (2a)$$

$$S_1 = E_x E_x^* - E_y E_y^* = 2C \qquad (2b)$$

$$S_2 = E_x E_y^* + E_y E_x^* = 2D \qquad (2c)$$

$$S_3 = i(E_x E_y^* - E_y E_x^*) = -B \qquad (2d)$$

where E_x and E_y are the optical field amplitudes. The Stokes parameters, which are real quantities expressed in terms of intensities, are appropriate for describing polarized or partially polarized light. S_0 is the total intensity, S_1 describes the amount of linear horizontal or vertical polarization, S_2 describes the amount of linear + 45° or- 45° polarization, and S_3 describes the amount of left or right handed circular polarization.

The setup for light collection and polarization measurement is shown schematically in Fig. 2(b). For a metal-metal tunneling junction, it was found by Berndt that the luminescence is peaked about a direction 30° from the sample surface [13]. The axis of our collection optics is along this direction. The collection lens accepts a solid angle of 0.2 sr. The light passes through a vacuum window selected for low birefringence. We use an achromatic quarter wave plate which, over the narrow energy range of interest from 1.4 to 2.2 eV, has a retardation of $0.25 \pm 0.01\lambda$. Bandpass or cutoff filters can be inserted for measurements in specified wavelength ranges, although the count rates were generally too low to use bandpass filters. No filters were used for the measurements reported in this paper. The final analyzer, which has the advantage of being fixed with respect to the detector in this method, is a Glan-Thompson polarizer . The avalanche photodiode is a single photon counting module with an active area 100 μm in diameter and a dark count rate of 10 counts/sec. A 16 mm long by 3 mm diameter Alnico 5 permanent magnet, which is mounted on the sample stage, provides a field of approximately 16 kA/m at the Fe whisker. This magnetic field is more than sufficient to overcome the demagnetization field of the whisker and saturate it; the field can be reversed by a current pulse through the windings around the Alnico core.

The nature of the measurement procedure is determined by the low photon count rates. In spite of a good detector efficiency of nearly 50% at 2 eV falling to 20% at 1.4 eV, the typical count rate is 100 Hz/nA. (The data reported is not corrected for detector sensitivity.) The count rate was tip dependent, and typically observed to vary from 30 Hz/nA to 300 Hz/nA at a bias voltage of 2 eV. Neither tunneling current nor bias voltage can be increased arbitrarily; we detected sample surface damage and tip instabilities at currents greater than 2 nA and bias voltages greater than 2.5 eV. These limits, like the count rates themselves, are very tip dependent. Thus, tip stability is a very important factor. In a typical measurement, the STM scans over a small region of a sample terrace while the quarter wave retarder is rotated step-wise and the light intensity measured. To determine the Stokes parameters it is only necessary to measure at 8 angles spaced 22.5° apart in the first 180° of rotation; however, we typically measure 32 angles over 360°. This improves the statistics and provides a check on stability since the intensity variation in the second half cycle should be the same as the first. The data reported here are from stable tips where errors in the intensity measurements are statistical in origin, owing to little systematic variation. The counting time at each angle to obtain a sufficiently small uncertainty in the Stokes parameters is typically 8 s. The base pressure of 4 x 10^{-9} Pa allowed measurements over many hours before the sample surface became contaminated.

Further demands are put on tip stability when attempting to measure small changes in circular polarization due to changes in the magnetization from +**M** to -**M**. The small permanent magnet could not be pulsed to reverse the magnetic field, and therefore the sample magnetization, while tunneling without causing tip or sample damage. Therefore, we retract the tip approximately one micrometer and then re-establish tunneling after magnetization reversal at a tip position typically within 5 nm of the previous position. Before and after the STM measurements, we check that the whisker magnetization switches in the applied field of an identical permanent magnet *ex situ* in an imaging Kerr microscope [14].

Results

Au(111)

Before discussing the possibility of obtaining magnetic contrast from the polarization measurements, we illustrate the technique with tunneling between W(111) and an Au(111) sample. Typical data is shown in Fig. 3(a) for tunneling at 2 nA and a sample bias of -2.0 V. The dominant variation is as cos(4Θ), which from Fig. 2(a) and Eqs. (1) and (2), means that the luminescence is mainly linearly polarized along the axis of the linear polarization analyzer. The analyzer axis was aligned close to the plane determined by the tip axis and the direction of the collected light. These results confirm the prediction that the light is linearly polarized as expected for radiation from the dipole formed by the tip and image charge in the sample [2,3]. Surprisingly, a small -sin(2Θ) component is also present, which causes the deeper minima at 45° and 225° and the lesser minima at 135° and 315°. This shows that a small part of the luminescence is right circularly polarized (negative helicity) light.

The data derived from curves like Fig. 3(a) taken at various sample bias voltages are plotted in Fig. 3(b). The bias voltage sets the maximum photon energy. Thus measurements as a function of bias voltage give a rough picture of changes with photon energy. We see from Fig. 2(b) that the luminescence is fully polarized over this range; that is, $(S_1^2 + S_2^2 + S_3^2)^{1/2} / S_0 = 1$ within experimental uncertainty. The intensity S_0 increases with increasing absolute bias voltage, in part due to higher detector efficiency at larger photon energies, but predominantly due to the increase in available phase space for the inelastic processes that cause the photon emission [13].

The circular polarization is also approximately constant over this range within experimental uncertainty. We believe the small circular polarization is due to tip asymmetries. The amount of circular polarization varies from experiment to experiment and sometimes changes during a single experiment. For our tips, this circular polarization was usually less than ±10%. This effect has been investigated recently by Vázquez de Parga and Alvarado [4]. Therefore, to determine if a circular polarization results from tunneling between W and Fe, it is necessary to reverse the magnetization to discriminate against the circular polarization produced by a tip asymmetry, and to do so without causing any changes in the tip.

Fe(100)

The Stokes parameters for STM-stimulated photon emission from the Fe(001)/W(111) tunneling junction were measured for both negative and positive sample voltages. Typically, data would be obtained at a few bias voltages with the Fe sample magnetized in one direction and then the magnetization reversed. This was repeated several times. Several runs (a run being measurements at 32 angles during one rotation of the quarter wave plate) at the same bias voltage and sample magnetization were added together to improve the statistics.

The results for Fe(001) are very similar to those for Au(111). The luminescence light is fully polarized within experimental uncertainty. It is primarily linearly polarized in the plane defined by the tip axis and light emission axis. The Fe data also show a small circular polarization component as seen in Fig 4, which is independent of sample bias. Most importantly, there is no change in the circular polarization that can be associated with a change in magnetization within an experimental uncertainty of approximately ± 2%. This is in agreement with a recent theoretical calculation [8]. The experimental uncertainty is highest at lower sample bias with corresponding lower maximum photon energy and lower count rates. At positive sample bias, somewhat fewer runs were added together leading to larger error bars.

Conclusions

We have measured the Stokes parameters to fully characterize the polarization of the

STM-induced luminescence for W(111) tips and samples of Au(111) and Fe(001). In both cases the luminescence is fully polarized within experimental uncertainty and predominantly linearly polarized as expected for dipole radiation. There is a tip-dependent circular polarization, which we attribute to tip asymmetries. We find no circular polarization that depends on the direction of magnetization of the Fe sample, in contrast to previous measurements on Co [3].

A number of factors make the measurement of the circular polarization of the luminescence *vs* sample magnetization difficult: 1) low count rates, 2) circular polarization from tip dependent asymmetries, and 3) necessity of protecting the tip during sample magnetization reversal. Because of these factors, we have not investigated other combinations of tip materials and ferromagnetic samples. We conclude that measuring the circular polarization of STM-stimulated photon emission from a metal-metal junction does not provide a general means to achieve magnetic contrast in STM.

Acknowledgements

We wish to thank J. Unguris for Kerr imaging measurements of the Fe(001) samples and D. R. Penn, M. D. Stiles, and P. Apell for helpful discussions. This work was supported in part by the Office of Naval Research.

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Figure Captions

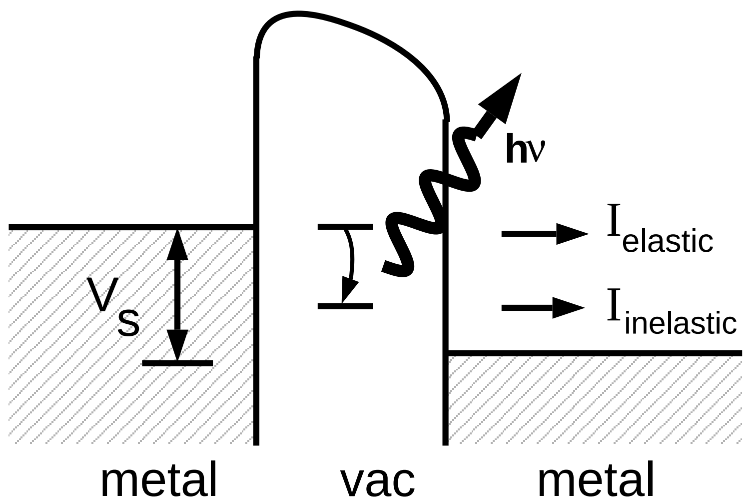
Fig. 1. Schematic of the inelastic tunneling process leading to photon emission in a metal-metal STM junction.

Fig. 2. a) Rotating quarter wave retarder/fixed linear analyzer technique for determining the Stokes parameters. b) Schematic of the experimental apparatus for polarization measurements of the STM-induced luminescence.

Fig. 3. a) Points are the raw data for tunneling at -2 V sample bias and 2 nA tunneling current for a W(111) tip and Au(111) sample measured for 8 s per point. The line is a plot of Eq. (1) with parameters determined from the data. b) At each sample bias, a run as in (a) yields the Stokes parameters. Plotted here are the total polarization $(S_1^2 + S_2^2 + S_3^2)^{1/2}$, the circular polarization S_3/S_0, and the total intensity S_0. The average total polarization is 0.99±0.02 and the average circular polarization is 0.09±0.01. The dashed lines are guides to the eye. The error bars in these figures represent $\pm\sigma$ statistical uncertainty. The values at a sample voltage of -2 V are derived from the data in (a).

Fig. 4. The circular polarization measured for tunneling between W(111) and Fe(001) as a function of sample voltage and sample magnetization is shown by the filled squares

and circles. The difference in the circular polarization on reversing the sample magnetization is plotted against sample voltage at the bottom. There is no magnetization dependent effect within experimental uncertainty.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$I_{elastic}$
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metal
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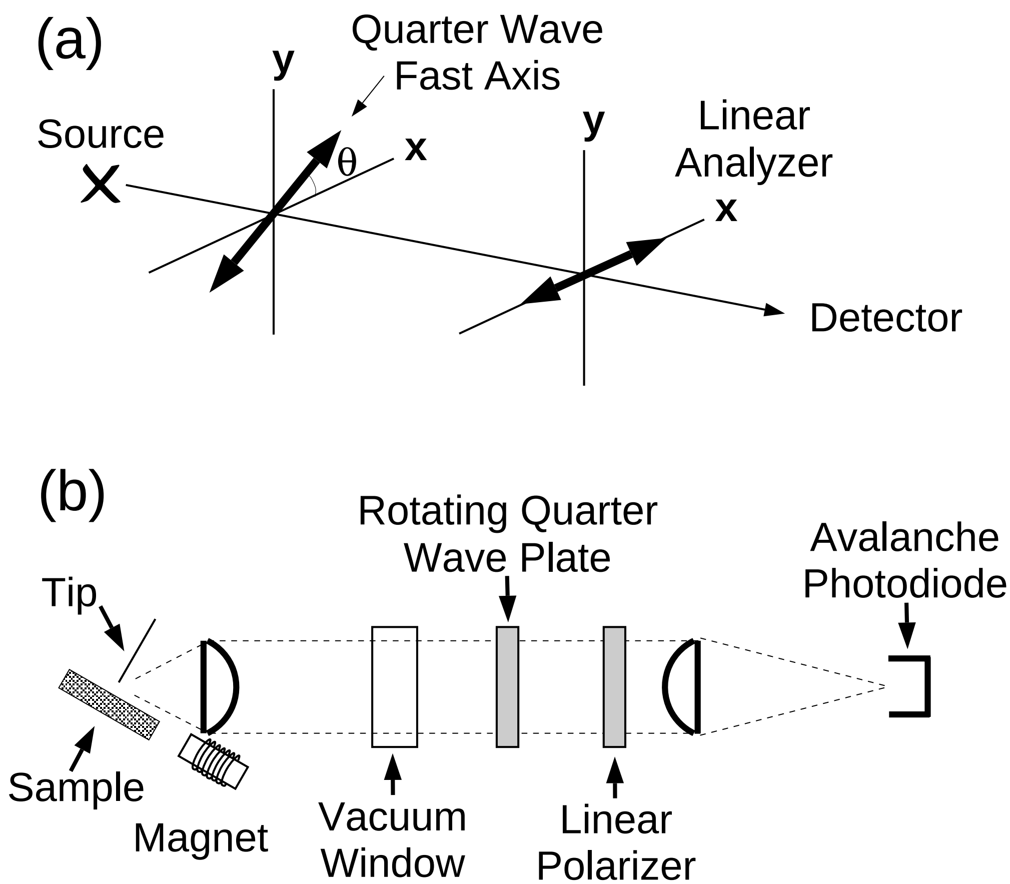
(a)
Quarter Wave
Fast Axis
y
Source
θ
x
y
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Analyzer
x
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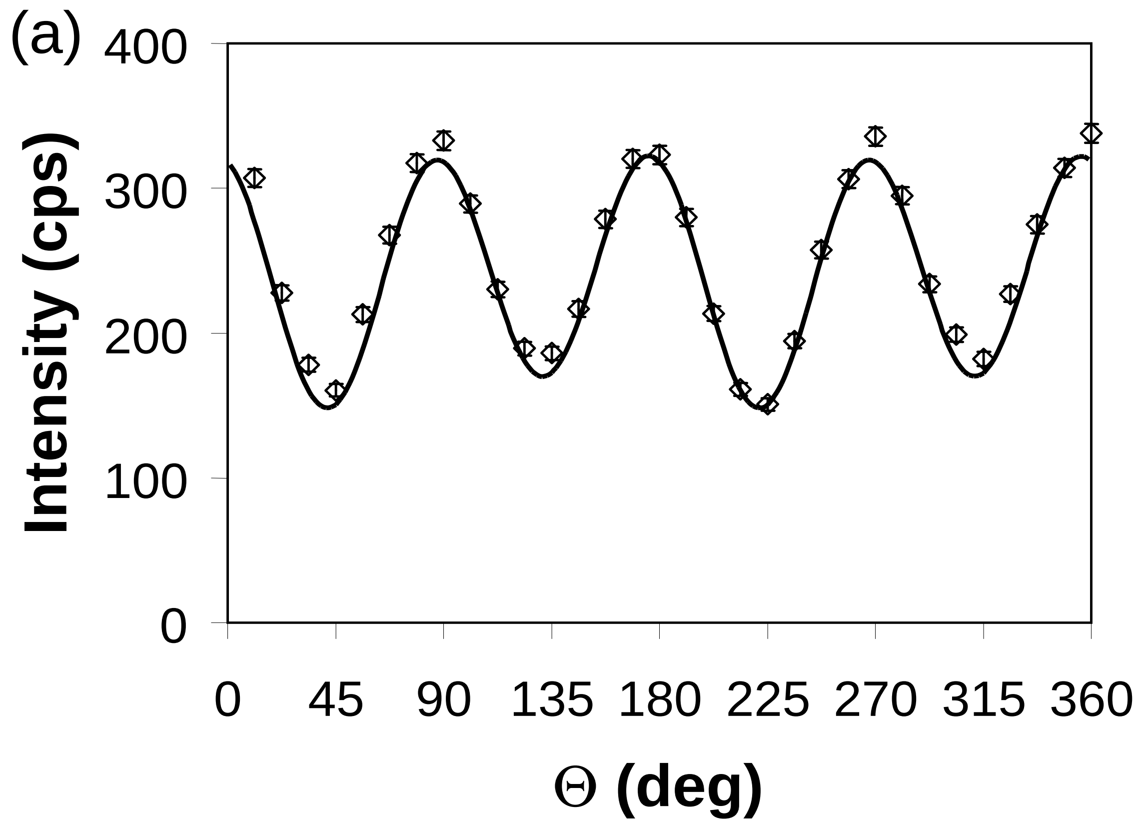
(b)
Rotating Quarter
Wave Plate
Avalanche
Photodiode
Tip
Sample
Magnet
Vacuum
Window
Linear
Polarizer


(a)
Intensity (cps)
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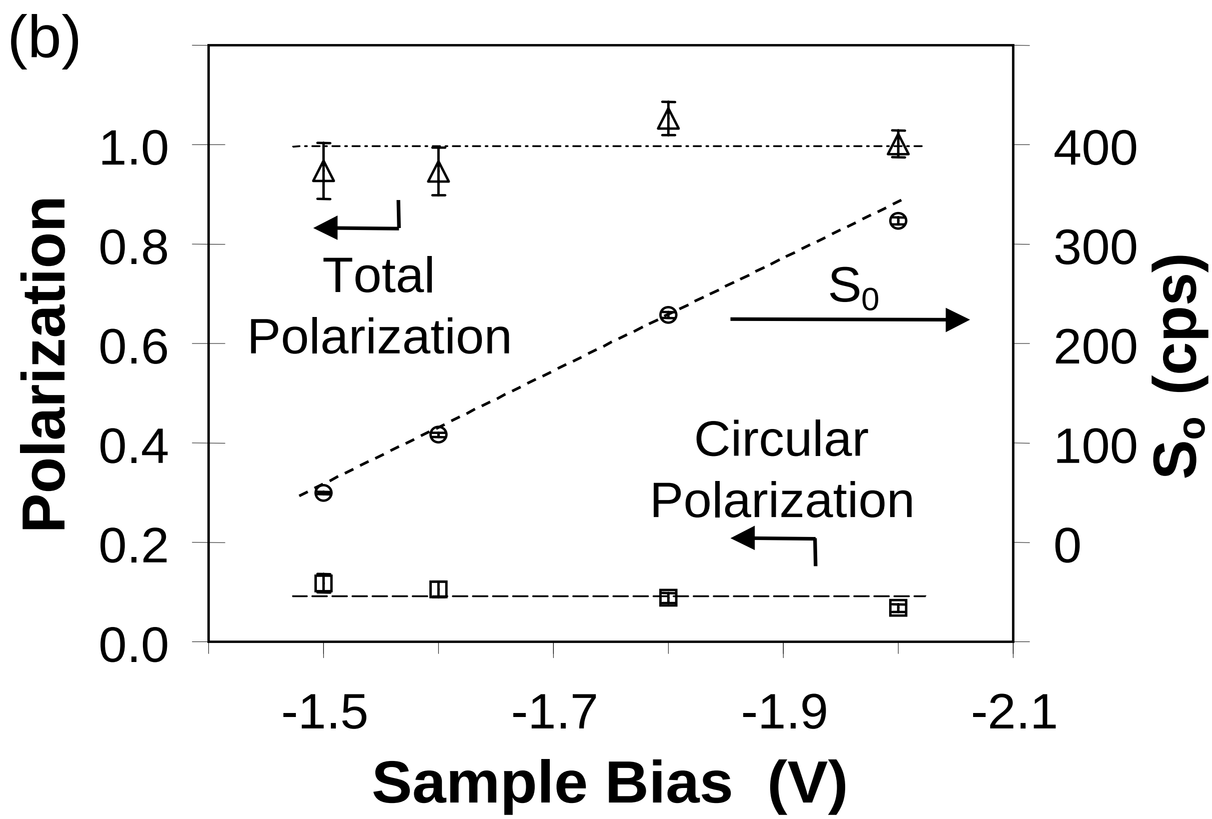
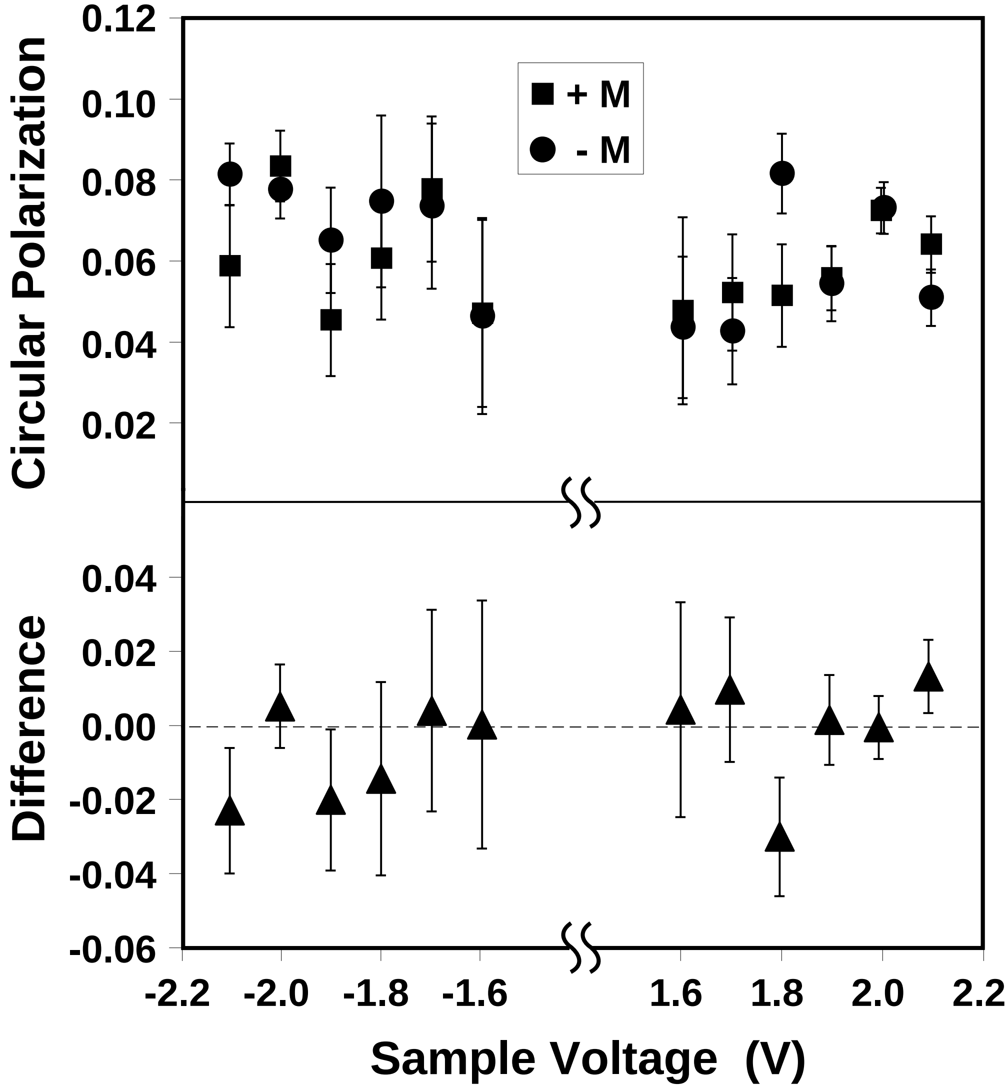
300
200
100
0
0
45
90
135
180
225
270
315
360
Θ (deg)


(b)
Polarization
1.0
0.8
0.6
0.4
0.2
0.0
Total
Polarization
S0
Circular
Polarization
400
300
200
100
0
So (cps)
-1.5
-1.7
-1.9
-2.1
Sample Bias (V)


Circular Polarization
0.12
0.10
0.08
0.06
0.04
0.02
+ M
- M
Difference
0.04
0.02
0.00
-0.02
-0.04
-0.06
-2.2
-2.0
-1.8
-1.6
1.6
1.8
2.0
2.2
Sample Voltage (V)