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THE POLARIZED LIGHT SCATTERING MATRIX ELEMENTS FOR SELECT
PERFECT AND PERTURBED OPTICAL SURFACES

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THE POLARIZED LIGHT SCATTERING MATRIX ELEMENTS
FOR SELECT PERFECT AND PERTURBED OPTICAL SURFACES

by
Vincent John Iafelice, Jr.

A Thesis Submitted to the Faculty of the
DEPARTMENT OF PHYSICS
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1985
STATEMENT BY AUTHOR

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ACKNOWLEDGMENTS

I would like to thank Dr. W. S. Bickel for his unending support and enthusiasm. He is always there when you need him.

I would like to thank all the members of our research group, past and present, especially Gorden Videen for his expert data collection and plotting software and Wilbur Bailey for advice received during the construction of the nephelometer used in this work.

I would like to thank Mary Long, Dr. J. Fordemwalt, and Ali Musallam for all the assistance received in the preparation of my samples.

I would like to thank Gary Chandler for expert advice regarding the SEM used in this work.

I would like to thank Jennifer Cole for always having an open ear and a ready backpack.

I would like to thank "The Tumors" for keeping the music alive.

I would like to thank Tom Whittemore for many Cu sputtering runs.

I would like to thank Barbara Bickel for her help in the preparation of this manuscript.

And finally, I would especially like to thank my family for their patience and encouragement over the years, and for learning to do without me so that I could do this work.
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ABSTRACT

The angular distribution of scattered light is known to depend on the electromagnetic properties (index of refraction, absorptivity), the geometrical properties (size, shape, and distribution) of the scatterer(s) as well as on the nature of the incident light. The entire 16 element Mueller matrix has been experimentally determined for a nominally smooth reflecting optical surface of aluminum which was illuminated with $\lambda = 441.6$ nm light at various angles of incidence. Additionally, a small rectangular line (whose known dimensions are of the order of the incident light) has been constructed of the same material (Al), on a similar surface. The Mueller matrix of the surface plus the line was measured as a function of the increasing size (height and width) of the line for various angles of illumination, $\alpha$. The experimental procedure and results are discussed and compared with existing theories.
INTRODUCTION

In many areas of technology, the angular distribution of scattered light from the microstructure of reflecting optical surfaces is of extreme interest. Such areas include the evaluation of machined metal mirrors for high energy laser applications and the entire industry concerned with the fabrication of conventionally polished mirror surfaces or the uses of such surfaces in complex optical systems. Scattered light reaching the image plane of such systems can significantly reduce resolution and image contrast. Light scattering is also used as a probe of the surface, i.e., remote sensing, non-destructive testing, monitoring surfaces for defects, defect counting, and characterizing or detecting changes in surfaces. Quantitative light scattering is related to quantitative surface structure. It is certain that progress in these new fields will come only with a better understanding of the scattering mechanisms.

When a parallel beam of light hits the smooth surface of a solid material, two limiting cases occur that describe the redistribution of the radiation. It is either specularly reflected (i.e., the angle of incidence is equal to the angle of reflectance) or it is "diffusely reflected" uniformly in all directions of the hemisphere. An example of these two extreme idealized cases are
shown in Figure 1.1, which compares the angular redistribution of light from a laser beam spot normally incident on an ideal reflecting (Fresnel) surface and an ideal matte (Lambert) surface.

The specularly reflected peak (a) appears at $\theta_i = \theta_r$ as a $\delta$-function $I = I_0 \delta(\theta - \theta_r)$. This says that ideally all the light is reflected into $\theta_r$ and no light appears at any other angle. The area under the $\delta$-function curve is proportional to the total energy/sec in the laser beam, neglecting absorption at the surface. The diffusely reflected signal (b) has no peak, i.e., it is flat over the entire $\theta$ range $0^\circ < \theta < 180^\circ$, $I = I_0 \times$ constant. Again the area under the curve is proportional to the total energy. We normalize it to equal the intensity of the $\delta$-function peak for convenience. A third curve (c) is drawn to represent some intermediate surface. It shows an intensity maximum at some angle, but redistributes light into all angles. All surfaces ideal, perfect, or real will create scattering signals that will fall somewhere between the two ideal curves. Our goal is to investigate some specific intermediate surfaces to see how curve (c) responds to known surface defects.

Now consider each of these limiting cases separately.

**Ideal Reflecting (Fresnel) Surface**

This simple case involves reflection at the surface of an absorbing medium. Therefore we modify the propagation equations for light in a transparent medium by replacing the real refractive index, $n_1$, by the complex index, i.e., $\bar{n}_1 = n_1 - ik_1$. The case for surface reflectance $R$ can be solved exactly only for the special case of
Figure 1.1. The angular redistribution of light from a laser beam spot normally incident on (a) an ideal reflecting surface, (b) an ideal matte surface, and (c) an intermediate surface.
normal incidence which gives,

\[
\bar{R}_p = \bar{R}_s = \frac{(n_s-n_i)^2 + k_i^2}{(n_s-n_i)^2 - k_i^2}
\]

where the subscripts \(p\) and \(s\) stand for the parallel and perpendicular components of polarization, respectively; \(n_s\) = the real refractive index of air; \(n_i, k_i\) = the real and real part of the imaginary indices of the metallic surface, respectively.

For incident angles other than normal incidence, exact reflectance expressions are cumbersome and approximations are often used. For example, many absorbing materials, particularly metals in the visible regions have \(n + k \gg 1\). With this approximation the reflectances reduce to

\[
\bar{R}_p = \frac{(n^2+k^2) \cos^2 \alpha - 2n \cos \alpha + 1}{(n^2+k^2) \cos^2 \alpha + 2n \cos \alpha + 1}
\]

\[
\bar{R}_s = \frac{(n^2+k^2) - 2n \cos \alpha + \cos^2 \alpha}{(n^2+k^2) + 2n \cos \alpha + \cos^2 \alpha}
\]

where \(\theta\) is the angle of incidence, measured from the normal.

The reflectance \(R\) is defined to be the ratio of the reflected to the incident flux or power. Percent reflectivities as a function of the angle of incidence for some typical materials are shown in Figure 1.2.
Figure 1.2. Percent reflectivities as a function of the angle of incidence for some typical materials.
Ideal Matte (Lambert) Surface

This case involves diffuse reflectance or scattering at a rough surface which can also be an absorbing medium. The first law of diffuse reflection was proposed by Lambert in 1760. It claims that the angular distribution of the reflected radiation is independent of the angle of incidence. It can be shown (Kortum 1969) for the case of an ideal matte surface that

\[
\frac{dI_r}{dA} = \left( \frac{C S_i}{\pi} \cos \alpha \right) \cos \theta = B \cos \theta
\]

where \( S_i \) = irradiation intensity for normal incidence (W/cm\(^2\)); \( B \) = surface brightness (W/cm\(^2\) str); and \( C \) = constant. In other words, the remitted scattered radiation flux per square centimeter and unit solid angle is proportional to the cosine of the incident angle, \( \alpha \), and to the cosine of the observation angle, \( \theta \). The constant \( C \) is the fraction of the incident radiation flux which is remitted. It is always less than 1, since some radiation is always absorbed. This relationship is called Lambert's Cosine Law.

Unfortunately, these two ideal limiting cases for a surface are never attained in practice. Even the best mirrors, such as a mercury surface, scatter the laser beam. The place where the beam hits can be seen, at all angles away from the reflected beam. A more realistic situation is indicated by Figure 1.3. This shows that the scattered light consists of a specular component plus a diffuse component which is scattered over a wide angular range centered about
Figure 1.3. Schematic representation of reflectance from a rough surface.
the Fresnel peak. The intensity distribution of light scattered by all real surfaces must fall somewhere between these two limiting cases.

Imperfect surfaces are characterized by surface roughness which can be the result of many kinds of defects formed during surface creation or preparation. For example, pits, scratches, and microsleeks are unavoidably generated on polished surfaces by particle abrasion and chemical attack that occurs during the polishing process. There are many ways to characterize these defects or roughnesses. For example, the rms surface height deviation, $\sigma$, of this random microroughness is routinely measured. It is typically 10 Å to 20 Å for polished surfaces (Bennett 1976) and 0.3 μm to 2.0 μm for ground glass surfaces (Kwon 1980). When such surfaces are then coated by evaporation or sputtering of various metals, they experience further degradation with the clumping of these metals on the surface during deposition (Heavens 1965).

There have been many attempts to relate the scattered light to the surface properties, i.e., roughness, defect number, kinds of defects, etc. The goal is to use light scattering signals to predict what the surface is and to monitor it for changes. Scattering of light from reflecting optical surfaces has been theoretically treated as diffraction (Harvey 1976) from the various randomly distributed surface defects just described. However in every case the experimental curves deviate somewhat from the theoretical curves, especially for large scattering angles. Thomas (1980) attributed these discrepancies to additional particulate contamination of the surfaces. No one has yet tried to characterize the scattered light
from "smooth reflecting optical surfaces" in terms of the complete polarization changes that occur in the incident light during the scattering process. Some studies (Thomas 1980) have examined certain linear polarizations, parallel or perpendicular to the scattering plane. None have examined the circular polarizations, which have been shown to be an extremely sensitive probe for the structural changes and time development of many scattering systems (Bickel and Stafford 1980).

This thesis presents the results of two studies:

1) The experimentally determined 16-element Mueller scattering matrix \( S_{ij}(\theta) \), comprising the total polarization information over a scattering angle from \( \theta = 0^\circ \) to \( 180^\circ \) for various angles of incidence from nominally smooth aluminized reflecting surfaces. We will refer to these surfaces as perfect mirror surfaces, or PMS.

2) The scattering matrix from these PMS on which a rectangular aluminum line (width \( = 1.0 \mu m \)) was fabricated using electron beam lithography (EBL) techniques.

Since the line presents additional geometrical possibilities, we studied the line as a function of illumination angle, \( \alpha \), as well as a function of its width and height. Theoretical treatment of a rectangular line on a surface is very complicated. The simplest theoretical treatment of this system would be to consider a plane electro-magnetic wave normally incident on the idealized geometry depicted in Figure 1.4.

If we neglect the microroughness of the surface (i.e., \( \sigma \ll \lambda \)) and consider only normal incidence, two scattering features — the
Figure 1.4. Idealized surface geometries showing surface microroughness ($\sigma$), perfect aluminum line, and Rayleigh half cylinder on a perfect mirror surface (PMS).
line and the mirror surface occur and will act as independent scatterers. Solving Maxwell's equations for this boundary value problem gives the resulting electric fields. From these, the Mueller matrix for this highly idealized situation can be derived. Considering either oblique incidence and/or the random microstructure that exists both on the line and mirror surface greatly complicates the problem because the two scattering features act as non-independent scatterers.

Lord Rayleigh (1907) considered the case of an infinitely long conducting half cylinder on an infinite conducting plane (see Figure 1.4). He used the method of images to get expressions for the parallel and perpendicular polarization components of the electric field in the far zone. Since the geometrical shape of the Rayleigh half cylinder is an approximation to the rectangular line, we can see how it compares to our data for our scattering system. Rayleigh experimentally measured the polarizations and found that theory and experiment did not fit at all angles, particularly near the specular peak. The disagreement between theory and experiment reported by Rayleigh and by others for such geometries is most likely due to misusing the image method. The method of images successfully treats electro-static cases, such as point charges and/or extended sources having an extremely high degree of symmetry. When this symmetry is absent, or when electric fields are time varying so that retardation is important, the image method does not work (Harris 1985). This was most recently verified by Nahm (1985) who used the image method to predict the scattering from dielectric spheres on an infinite conducting
plane (an Al mirror). His work also showed large discrepancies between theory and experiment for the same reasons noted above.

If the microroughness on the surface is kept much less than the wavelength \(\lambda\) of the incident light one is immediately tempted to compare the line on a plane to that of a diffraction grating with "one groove". The intensity distribution for an "ideal grating" is given by (Jenkins and White 1976):

\[
I = a^2 \frac{\sin^2(N\delta/2)}{\sin^2(\delta/2)} = a^2 \frac{\sin^2\gamma}{\sin^2\gamma}
\]

where \(\gamma = \delta/2 = \pi d/\lambda \sin \theta\); \(a\) = amplitude contribution by the individual slits; \(N\) = the number of grooves; and \(d\) = the groove spacing. With \(N = 1\) this reduces to,

\[
I = a^2
\]

where \(a^2\) represents the intensity diffracted by a single slit. Using the relation for the intensity distribution of a single slit,

\[
I = a^2 = A_s^2 \frac{\sin^2 \beta}{\beta^2}
\]

(1.1)

where \(A_s\) = the maximum intensity value; \(\beta = \pi b/\lambda (\sin \theta + \sin \alpha)\); \(b\) = the slit width; \(\alpha\) = the angle of incidence; and \(\theta\) = observation or scattering angle. Note that the relations for the single slit and one groove grating are identical. How good does the single slit and one groove grating formulae predict what occurs for a line on a mirror? One of the signals we measure is exactly this total intensity
distribution. We will show how good it is and that it is just one of
16 measurements we can make.

In general, we have found it advantageous in our experimental
light scattering research to take perfect geometrical scatterers as
our starting point. These can be treated exactly by theory. Defects
are added slowly and are treated as perturbations. This thesis is an
experimental investigation of scattering from the limiting case of a
perfect mirror surface (PMS), and the scattering from an idealized
geometrical "perturbation" fabricated on top of this PMS. Idealized
systems must be studied first. When they are well understood they
can be gradually degraded to create some of the irregular scattering
systems that exist in the real world. This approach will lead to a
better understanding of light scattering from complex scatterers.
A MATHEMATICAL DESCRIPTION OF POLARIZATION

The Stokes Parameters

The polarization state of a beam of light (either unpolarized, totally, or partially polarized) can be described in terms of quantities known as the Stokes parameters. We will first define the parameters operationally and then relate them to electromagnetic theory.

Consider a set of four filters each of which, under natural (unpolarized) illumination, will transmit one half of the incident light, and discard the other half. Let the first filter be simply isotropic, passing all states equally (total intensity = all the light transmitted). The second and third are linear polarizers whose transmission axes are horizontal and at +45° respectively. The last filter is a right circular polarizer opaque to left handed states. Each one of these four filters can be placed in the beam under investigation while the transmitted irradiances $I_0$, $I_1$, $I_2$, $I_3$ are measured with a meter insensitive to polarization. Note if the total intensity $I$ is 100% linearly polarized at 45°, then $I_3 = I_1$ with $I_0 = I_2 = 0$. The operational definition of the Stokes parameters is then given by the relations (Hecht and Zajac 1979):
In these equations, $I$ is simply the incident irradiance while $Q$, $U$, and $V$ specify the state of polarization, i.e., $Q$, $U$, and $V$ are the intensities of a particular polarization state. Thus $Q$ reflects a tendency for the polarization to more nearly resemble either a horizontal ($Q > 0$) or vertical ($Q < 0$) polarization state. When the transmitted beam is independent of the orientation of these axes, i.e., if $Q = 0$, the beam polarization may be elliptical at ±45°, circular, or unpolarized. Similarly $U$ reflects a tendency for the light to more closely resemble a polarization state oriented either in the +45° ($U > 0$) or −45° ($U < 0$) direction, or neither ($U = 0$). Similarly $V$ reflects a tendency of the beam toward right handedness ($V > 0$) or left handedness ($V < 0$) or neither ($V = 0$).

Now recall the expressions for quasimonochromatic light,

$$
\overline{E}(t) = \overline{E}_e(t) \exp(ikz-\omega t)
$$

and

$$
I = \varepsilon_s c \langle \overline{E}^2(t) \rangle
$$

where

$$
\overline{E}_e(t) = E_x(t)x + E_y(t)y
$$

$$
E_x(t) = a_x(t) \exp(-i\delta(t))
$$

$$
E_y(t) = a_y(t) \exp(-i\delta(t))
$$

$a(t) = \text{amplitude of the electric field}$
\( \varepsilon_0 \) = permittivity of free space  
\( c \) = speed of light in a vacuum  
\( k = 2\pi/\lambda \); \( \lambda \) = wavelength of light  
\( \omega \) = angular frequency of light

By straightforward application the Stokes parameters can be rewritten as

\[
\begin{align*}
I &= \langle ExE_x^* + EyE_y^* \rangle = \langle ax^2 \rangle + \langle ay^2 \rangle \\
Q &= \langle ExE_x^* - EyE_y^* \rangle = \langle ax^2 \rangle - \langle ay^2 \rangle \\
U &= \langle EyE_y^* + ExE_x^* \rangle = \langle 2axay \cos \delta \rangle \\
V &= \langle i(ExEy^* - EyEx^*) \rangle = \langle 2axay \sin \delta \rangle \\
\end{align*}
\]

(2.1)

where \( \delta(t) = \delta_x(t) - \delta_y(t) \).

For example,

\[
I_s = \frac{1}{2} I_{\text{incident}} = \frac{1}{2} \varepsilon_0 c \langle E^2(t) \rangle \\
= \frac{1}{2} \varepsilon_0 c \langle E_x^2 \cos^2 (kz-\omega t) + E_y^2 \cos^2 (kz-\omega t) \rangle \\
= \frac{1}{2} \varepsilon_0 c \langle a_x^2 \rangle \langle \cos^2 (kz-\omega t) \rangle + \frac{1}{2} \varepsilon_0 c \langle a_y^2 \rangle \langle \cos^2 (kz-\omega t) \rangle \\
= \frac{1}{4} \varepsilon_0 c [\langle a_x^2 \rangle + \langle a_y^2 \rangle] \\
\]

Therefore

\[
I = 2I_s = \frac{1}{2} \varepsilon_0 c [\langle a_x^2 \rangle + \langle a_y^2 \rangle] \\
\]

In Eqs. (2.1) above, the constant \( \varepsilon_0 c/2 \) has been dropped so that the Stokes parameters are now proportional to irradiances (Watt/cm\(^2\)).
Also, for the case of perfectly monochromatic light, $a_x(t)$, $a_y(t)$, and $\delta(t)$ are time independent and one need only drop the $< \, >$ brackets in Eqs. (2.1) to get the applicable Stokes parameters.

It is convienent to normalize the Stokes parameters by dividing each one by the total intensity, $I$. This puts the incident beam at unit irradiance. The set of parameters, arranged in the form of a vector, $|I, Q, U, V|$, for unpolarized light in this normalized representation is then $|1, 0, 0, 0|$. It also follows from Eqs. (2.1) that $I^2 \ge Q^2 + U^2 + V^2$ where the equality holds for totally polarized light and the inequality holds when an unpolarized component is present. For partially polarized light the fraction of polarization is given by

$$\pi = \left( \frac{Q^2 + U^2 + V^2}{I} \right)^{1/2}.$$

The Mueller Matrices

In 1943 Hans Mueller, then a professor of physics at MIT, devised a matrix method for dealing with the Stokes vectors. Optical devices are represented by 4x4 Mueller matrices that convert one Stokes vector into another. Let $[M]$ represent the transformation matrix of the optical element in question. Then

$$|V'| = [M] |V|,$$

where $|V|$ is the Stokes vector of the input beam and $|V'|$ is the Stokes vector of the outgoing beam.
As an example we will construct \( [M] \) for a horizontal linear polarizer. We do this by forcing \( [M] \) to convert any kind of light into horizontally polarized light.

a) Let \( [M] \) convert unpolarized light into horizontally polarized light with 1/2 the incident irradiance:

\[
\begin{bmatrix}
1 \\
1/2 \\
0 \\
0
\end{bmatrix} = \begin{bmatrix}
a_{11} & a_{12} & a_{13} & a_{14} \\
a_{21} & a_{22} & a_{23} & a_{24} \\
a_{31} & a_{32} & a_{33} & a_{34} \\
a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix} \begin{bmatrix}
1 \\
0 \\
0 \\
0
\end{bmatrix}
\]

We get

\[
a_{11} = a_{21} = 1/2 \quad \text{and} \quad a_{31} = a_{41} = 0.
\]

b) \( [M] \) converts horizontally polarized light to a horizontal polarization state. In this case the total irradiance is transmitted:

\[
\begin{bmatrix}
1 \\
1/2 \\
0 \\
0
\end{bmatrix} = \begin{bmatrix}
1/2 & a_{12} & a_{13} & a_{14} \\
1/2 & a_{22} & a_{23} & a_{24} \\
0 & a_{32} & a_{33} & a_{34} \\
0 & a_{42} & a_{43} & a_{44}
\end{bmatrix} \begin{bmatrix}
1 \\
1 \\
0 \\
0
\end{bmatrix}
\]

We get

\[
a_{12} = a_{22} = 1/2 \quad \text{and} \quad a_{32} = a_{42} = 0.
\]
c) \([M]\) converts +45° polarized light to a horizontal polarization state with 1/2 irradiance:

\[
\begin{bmatrix}
1/2 & 1/2 & a_{11} & a_{14} \\
1/2 & 1/2 & a_{21} & a_{24} \\
0 & 0 & a_{31} & a_{34} \\
0 & 0 & a_{41} & a_{44}
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
1/2+a_{11} \\
1/2+a_{21} \\
a_{31} \\
a_{41}
\end{bmatrix}
\]

We get

\[a_{11} = a_{21} = a_{31} = a_{41} = 0\]

\[d) \quad [M] \text{ converts right circularly polarized light to a horizontal polarization state with 1/2 irradiance.}\]

\[
\begin{bmatrix}
1/2 & 1/2 & 0 & a_{11} \\
1/2 & 1/2 & 0 & a_{21} \\
0 & 0 & 0 & a_{31} \\
0 & 0 & 0 & a_{41}
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
1/2+a_{11} \\
1/2+a_{21} \\
a_{31} \\
a_{41}
\end{bmatrix}
\]

We get

\[a_{11} = a_{21} = a_{31} = a_{41} = 0\]

Putting all of this together we see that a horizontal linear polarizer must have a matrix \([M]\) given by
The matrices of any optical element can be generated in a similar manner. The Mueller matrix - Stokes vector method is a powerful way to characterize polarization states of any light beam, especially for beams passing through optical systems involving several polarizing elements. If a beam $|V|$ passes through a series of optical elements represented by matrices $[M_1] [M_2] ... [M_n]$ then the final beam is

$$|V'| = [M_n] ... [M_2] [M_1] |V|$$

Since the matrices do not commute, they must be applied in the proper order.

**The Scattering Matrix**

In general, the characteristic Mueller scattering matrix $[S]$ for any scatterer or scattering system is a 4x4 array of 16 elements $S_{ij}(\theta)$, each of which is a function of the scattering angle $\theta$. For isotropic, symmetric scatterers (either single or collections) with mirror symmetry only 4 of the 16 elements are unique, the others being either zero, negatives, or identical. To start with we will assume $[S]$ has no zero elements, to allow for all possible mixing of polarization states.

A scatterer changes the state of the incoming polarized light by mixing the components of the incident electric field vectors
\(E_x, \ E_y\). These are the initial components parallel and perpendicular to the scattering plane, respectively. The new parallel and perpendicular electric field components \(E'_x, \ E'_y\) come from the amplitude transformation equations for the electric field given by

\[
E'_x = A_2E_x + A_3E_y \\
E'_y = A_4E_x + A_5E_y
\]

or

\[
\begin{bmatrix}
E'_x \\
E'_y
\end{bmatrix} =
\begin{bmatrix}
A_2 & A_3 \\
A_4 & A_5
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
\]

The scattering matrix is derived by substituting these amplitude transformation equations for the electric field into the Stokes parameters and solving for the elements of the \(4 \times 4\) intensity transformation matrix. The general form of the scattering matrix is given by van de Hulst (1957) and is applicable to any scattering system. For symmetric scatterers, where no mixing of the \(E_x\) and \(E_y\) occurs in the scattered light, \(A_3 = A_5 = 0\). For this situation the scattering matrix can be written as

\[
[S] = \begin{bmatrix}
1/2(a_1^2 + a_2^2) & 1/2(a_2^2 - a_1^2) & 0 & 0 \\
1/2(a_2^2 - a_1^2) & 1/2(a_1^2 + a_2^2) & 0 & 0 \\
0 & 0 & \Sigma_{21} & -D_{21} \\
0 & 0 & D_{21} & \Sigma_{21}
\end{bmatrix}
\]

where

\[A_kA_k^* = |a_k|^2\]
\[
\frac{1}{2}(A_j A_k^* + A_k A_j^*) = |a_j| |a_k| \sin \delta = \Sigma_{jk}
\]
\[
\frac{1}{2}(A_j A_k^* - A_k A_j^*) = |a_j| |a_k| \cos \delta = D_{jk}
\]
\[a_i \ (i = j \text{ or } k) \ = \ \text{amplitude of the electric field} .\]

To get a physical feel for the elements \( S_{ij} \) of the scattering matrix, let the general matrix \([S]\) be illuminated by a light beam defined by an arbitrary Stokes vector. We have

\[
V' = \begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\begin{bmatrix}
I \\
Q \\
U \\
V
\end{bmatrix} = \begin{bmatrix}
S_{11}I + S_{12}Q + S_{13}U + S_{14}V \\
S_{21}I + S_{22}Q + S_{23}U + S_{24}V \\
S_{31}I + S_{32}Q + S_{33}U + S_{34}V \\
S_{41}I + S_{42}Q + S_{43}U + S_{44}V
\end{bmatrix}
\]

The output Stokes vector components are linear combinations of the input Stokes vector components, each weighted by the appropriate Mueller scattering matrix element. Each element is therefore a measure of how much of a particular input component is converted by the scatterer into a particular output component as a function of the scattering angle \( \theta \). For example, matrix element \( S_{14}(\theta) \) describes how much of the incident right hand circular light appears as \( +45^\circ \) linear light as a function of \( \theta \). It is essentially a measure of how much the scatterer acts as a quarter-wave retarder or, equivalently, how much of \( V \) is converted into \( U \) (or \(-U\)).
CHAPTER 3

THE LIGHT SCATTERING INSTRUMENT

The type of instrument used in this work is called a polar nephelometer. For a more complete discussion of its design and operation see Hunt and Huffman (1973), Bickel et al. (1976), and Bell (1981). Figure 3.1 is a block diagram of the polar nephelometer and the surrounding electronics. Light from a 16 mWatt He-Cd laser (\(\lambda=4416\AA\)) passes through a variable neutral density filter which controls the beam intensity and then through a spatial filter-lens system which adjusts the laser beam profile and spot size and focuses it on the sample. It then passes through a linear polarizer-photoelastic modulator combination and then through a series of pinhole apertures before it is allowed to strike the sample. The input linear polarizer (ILP) and the modulator are mounted as a single unit since all measurement orientations require a relative angle of 45° between the two respective axes. The photoelastic modulator is the heart of the nephelometer system and will be described more completely in the following sections.

The light scattered by the sample is detected by a photomultiplier tube (RCA 1P21) mounted in an aluminum casing on an arm which can be rotated through an angle from 0° to 167° by a dc motor. Analyzing optics such as laser line filters, polarizers, \(\lambda/4\)
Figure 3.1. Schematic diagram of the experimental set up.
retarders and slit apertures can be placed in a tray constructed on this arm in front of the detector. The ac component of the PMT signal is detected by a lock-in amplifier (PAR HR-8) and sent through an analog to digital converter (ADC) to an Imsai 8080 computer for storage and handling. The dc component of the output is switched into one of two channels depending on the desired mode of operation. It may be measured directly by a logarithmic amplifier (Keithley 26000) and then sent to computer, or it may be passed through a picoammeter which drives a control circuit. More will be said of the nephelometer electronics later.

The sample mount consists of an x-y-z translator, tilt positioners, and rotational mounts, so that both the position of the sample its tilt, \( T \), and the angle of incidence, \( a \), can be adjusted. The relationship among the various parameters is described in Figure 3.2. The mirrors under investigation were glued to the face of microscope slides which had been previously painted flat black to prevent light transmission through the back side. These slides were mounted in a holder and positioned over the rotational axis of the nephelometer arm. Adjustments were made to get perfect alignment with respect to the laser beam and scattering angle.

In order to prevent saturation of the photomultiplier tube (PMT) at \( \theta = 0^\circ \), and during the first few degrees of the scan, the straight through laser beam is blocked by a beam stop made of a black plastic tapered tube.

The entire apparatus with the exception of the laser, spatial filter, variable neutral density filter, and modulator assembly is
Figure 3.2. Relationship between the various sample orientation parameters.
enclosed in a light-tight box with an opaque curtain covering the access door. Mirrors were positioned at various places on the inside walls of the box in order to direct the specularly reflected beam into a second beam stop. This light would otherwise be scattered off the walls and perhaps reach the detector.

**Polarization Modulation Techniques**

A technique developed by Hunt and Huffman (1973) uses a polarization modulated input beam and lock-in detection to produce the various scattering matrix elements $S_{ij}(\theta)$. The modulation technique effectively varies the input polarization so that the various harmonics of the signal detected are proportional to the matrix elements.

**The Modulator**

The photoelastic modulator consists of a vibrating block of amorphous quartz which is driven at its natural frequency (50 kHz) by a piece of crystalline quartz of similar proportions. The applied stress in the amorphous quartz induces a periodic birefringence which, if of the right amplitude, could modify the polarization state of the incoming light from linear to alternately right and left circularly polarized depending on the modulator axis. Let the phase retardance be $\delta$. Then

$$\delta(t) = s \left( \frac{2\pi d}{\lambda} \right) \sin \omega t = A \sin \omega t , \quad (3.1)$$

where $\lambda =$ wavelength of transmitted light; $d =$ thickness of the slab;
s = stress coefficient; and \( \omega \) = resonant frequency of the slab (50 kHz). Since the time varying phase retarder causes time varying polarization of the incident beam, the signal from the scattered light contains harmonics which are proportional to different input polarizations and as such carry information about the matrix elements.

Consider the arrangement of the ILP at \( +45^\circ \) with modulator fast axis at \( 90^\circ \). The Mueller matrix for a linear phase retarder oriented with fast axis at \( 90^\circ \) is

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \cos \delta & -\sin \delta \\
0 & 0 & \sin \delta & \cos \delta
\end{bmatrix}
\]

where \( \delta \) = retardance. Therefore the combination of the ILP[+45°] and the [Mod 90°] is given by

\[
|V|_1 = [\text{Mod } 90^\circ] \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} I = I \begin{bmatrix} 1 \\ 0 \\ \cos \delta \\ \sin \delta \end{bmatrix}
\]

where \( |V|_1 \) = Stokes vector of beam incident on the scatterer and \( I \) = irradiance after the ILP. The Stokes vector emerging from the scatterer \( |V|_e \) is
Finally the Stokes vector reaching the detector is given by

\[ |V|_{\text{DET}} = [\text{FLP} + 45^\circ] |V|_e = I/2 \]

or

\[ I_{\text{DET}} = \frac{1 + \frac{S_{11} + S_{13}}{S_{11} + S_{13}} \cos \delta + \frac{S_{14} + S_{24}}{S_{11} + S_{13}} \sin \delta}{S_{11} + S_{13} + (S_{11} + S_{13}) \cos \delta + (S_{14} + S_{24}) \sin \delta} R \]

where \( R \) = response of the PMT.

**Lock-in Detection and Electronics**

The dc portion of the PMT signal is separated electronically and fed to a servo mechanism which controls the PMT high voltage. This servo mechanism is referred to as a constant current servo (CCS) since it enables one to demand a certain current from the PMT by servoing the PMT high voltage. This effectively divides the detector
signal by the dc component so that the current from the detector is given by Eq. (3.2) above. The ac portion of this signal goes through a preamp and then into the lock-in amplifier which is tuned to pick out the desired harmonic component. From Eq. (3.1) we see that the phase retardance is a sinusoidal function of time, but it occurs as an argument of the trigonometric functions in Eq. (3.2). Expanding \( \sin \delta \) and \( \cos \delta \) in terms of Bessel functions, we get

\[
\sin \delta = \sin (A \sin \omega t) = 2 J_1(A) \sin \omega t + 2J_3(A) \sin 3\omega t + \ldots
\]

\[
\cos \delta = \cos (A \sin \omega t) = J_0(A) + 2J_2(A) \cos (2\omega t) + \ldots
\]  \hspace{1cm} (3.3)

Inserting Eq. (3.3) into Eq. (3.2) yields

\[
I_{\text{DET}} = C_1 \left[ 1 + \frac{S_{11} + S_{31}}{S_{11} + S_{31}} C_2 \cos 2\omega t - \frac{S_{11} + S_{31}}{S_{11} + S_{31}} C_3 \sin \omega t \right]
\]

where \( C_1, C_2, \) and \( C_3 \) are constants. When the lock-in is tuned to \( \omega_s (=50 \text{ kHz}) \) the amplified signal will be proportional to

\[
\frac{S_{11} + S_{31}}{S_{11} + S_{31}} \equiv S_{31}^*
\]

When tuned to \( 2\omega (=100 \text{ kHz}) \) the signal is proportional to

\[
\frac{S_{11} + S_{31}}{S_{11} + S_{31}} \equiv S_{33}^*
\]
In practice, the calibration procedure effectively sets the constant in front of the matrix element combinations equal to one, making the lock-in signal identically equal to the matrix element combinations listed above.

The Experimental Matrix $S_{ij}(\theta)$

Figure 3.3 shows the orientations of the input and analyzing optics required to measure each matrix element along with the combinations of elements measured. Below this is the lock-in reference frequency required for that measurement. All combinations of matrix elements obtained here are worked out in detail by Bell (1981).

For symmetric scatterers, $S_{\|\|} = S_{\perp\perp} = S_{\perp\|} = 0$. Therefore, for the cases discussed in the previous section,

$$S_{\|\|}^* \equiv S_{\|\|}/S_{\|\|} \quad \text{and} \quad S_{\perp\perp}^* \equiv S_{\perp\perp}/S_{\|\|}$$

i.e., $S_{\|\|}^*$ and $S_{\perp\perp}^*$ are equal to a normalized $S_{\|\|}$ and $S_{\perp\perp}$, respectively.

The four unique matrix elements that will be examined in this thesis are

$$S_{11}, \quad S_{12}^* = S_{12}/S_{11}, \quad S_{21}^* = S_{21}/S_{11}, \quad S_{22}^* = S_{22}/S_{11}.$$

All other matrix elements ($S_{ij}^*$) can be shown (Bell 1981) to be either zero, identical, inverses, or combinations of these four matrix elements, for the case of symmetric scatterers. Therefore, these
Figure 3.3. Orientations of the optical elements required to measure $S_{13}$. 
four unique matrix elements make up the entire matrix \([S_{ij}]\) which contains the total information accessible to elastic light scattering techniques (at this wavelength).

**Calibration**

Calibrating the instrument is relatively easy since most of the measurements are normalized. Our choices of the calibration orientations and lock-in resonance frequencies are shown in Figure 3.4. To calibrate for full scale deflection for a particular polarization it is necessary to insert only a linear polarizer or \(\lambda/4\) retarder into the exit beam when the detector arm is set at 0° (straight through beam with no scatterer in the beam path). The modulator amplitude, CCS, and lock-in settings are then adjusted to produce a full scale (100%) calibration of the lock-in.

The time averages of the \(\sin \theta\) and \(\cos \theta\) terms in Eq. (3.3) are zero and \(J_0(\lambda)\) respectively. To simplify the data interpretation it is convenient to make \(J_0(\lambda)\) equal to zero. This is accomplished by adjusting the modulator amplitude so that \(\lambda = 138^\circ\), which corresponds to the first zero of the \(J_0(\lambda)\) function. In practice this is done by rotating the analyzing polarizer \(\pm 90^\circ\) to obtain a \(\pm 100\%\) swing on the lock-in. This restriction fixes \(\lambda\) for each wavelength used, see Hunt and Huffman (1973) and Bell (1980).

**The Variable Neutral Density Filter (NDF)**

A variable NDF is used to reduce the intensity of the beam to normal operating levels in order to avoid damage to the PMT during calibration. The ac calibration signal (the polarization signal) is
Figure 3.4. Calibration orientations.
adjusted to +100% by requiring a certain dc current from the tube when the optics are set in the calibration mode. This is done by adjusting the CCS to get the required current. When calibration is done, at a certain voltage, the entire θ-scan should be made keeping this voltage constant or nearly constant throughout the scan. The normalized measurements are made by keeping the selected dc current constant by varying the high voltage to the PMT as the total intensity fluctuates. Ideally the voltage should not vary too far out of the calibration range even though in principal the current will stay constant at any voltage. To keep the voltage fluctuations in a narrow range a variable NDF was used. This eliminated variations in the PMT signal due to differences in the ac and dc gains and dark currents at different operating voltages by maintaining the PMT high voltage in the range set at the time of calibration. To determine the linear range of the PMT, we measured the "dark current" (noise) of the PMT as a function of HV on the PMT. We also measured how a small signal (at low intensity) along with the signal out of the PMT behaves as a function of HV. Both measurements show that the linear range of the tube is between -400 to -1000 volts. This range that the best response and S/N ratio of the tube is obtained.

For all the total intensity measurements in this thesis the laser was adjusted to maximum intensity and the high voltage on the PMT set to -800 V. The laser intensity on the sample was then dropped two orders of magnitude by inserting a No. 2 NDF, to keep the high voltage in the linear range of the PMT, i.e., HV = - 600 V. During the polarization measurements, the PMT voltages were
maintained at -600 V ± 100 V with a variable NDF inserted in the beam path. This ensures that the calibration remained intact during measurements despite large fluctuations of the total scattered irradiance.
CHAPTER 4

SAMPLE PREPARATION

Since we want to measure the Mueller scattering matrix for perfect mirrored surfaces (PMS), we took great care in the preparation of these surfaces. In fact, the preparation of quality surfaces turned out to be the most tedious and time consuming aspect of the entire thesis.

In addition to the PMS, we also fabricated aluminum lines (whose geometries are depicted in Figure 1.4) on top of these surfaces. In order to draw meaningful conclusions from our data it was extremely important that the dimensions of these lines be held within tight, predetermined specifications. Electron beam lithography (EBL) techniques were chosen because no other lithography method available could provide the type of precision demanded by us for geometrical line width control in the 1 µm range.

The Aluminum Mirrors

In modern times aluminum has become one of the most common metals in the industrialized world. Aluminum is highly reflecting at all visible wavelengths and into the ultraviolet, making it the commonly used coating for high quality mirrors. Although aluminum oxidizes readily, the oxide coating inhibits further deterioration by oxidation. This preserves the quality of the surface for most optical
applications because the oxide is transparent to visible light. These properties make aluminum the most widely chosen material for reflectance coatings, and an excellent choice for our studies.

Films of evaporated aluminum exhibit several other properties that are important to our work:

1) It was observed by Picard and Duffendack (1965) that evaporated aluminum surfaces crystalize to form agglomerates separated by interstices which are much, much narrower than the diameters of the aggregates. They go on to classify evaporated Al films as one of the least granular of all the metals, for many choices of substrates.

2) Aluminum is an excellent conductor; therefore the skin depth of this material is extremely small (≈ 700 Å for visible light). This property of aluminum enables us to deposit a very thin film with high opacity. This minimizes the material clumping that will occur with thicker depositions.

3) Aluminum is easily obtained having "5 nines" purity, i.e., 99.999% pure Al.

The aluminum mirrors used were prepared at the Optical Sciences Center thin films laboratory at The University of Arizona. They were manufactured by evaporating an optically thick (≈ 1200 Å thickness) layer of Al on to the surface of synthetic sapphire (Al2O3). To get high quality mirrors, we had to evaporate Al on high quality surfaces. We found that surfaces of synthetic sapphire have several properties that were important for our work:
1) Sapphire is extremely hard and scratch resistant.

2) Sapphire is virtually chemically inert, even at high temperatures.

3) Sapphire is an excellent thermal conductor and has a low mean linear expansion coefficient; therefore it will not expand with the high temperatures that occur during evaporation.

The sapphire substrates used in these experiments, purchased from Insaco Inc., have been diamond polished so that the rms height of the surface roughness ($\sigma$) falls between 5 and 25 Å. Standard optical cleaning procedures were used on the sapphire before coating to ensure good adhesion of the Al film and to maximize the smoothness (or specularity) of the resulting mirrors. Optical profile measurements of the polished sapphire taken before and after coating gave rms surface roughness values identical within the $\pm 3$ Å reproducibility estimates of the instrument. Optical profile measurements taken on a Wyko Digital Optical Profiler NCP-1000 M are shown in Figure 4.1. These data show that the PMS are as smooth as the original sapphire substrates, both surfaces having $\sigma = 16$ Å $\pm 3$ Å.

**Electron Beam Lithography (EBL)**

Traditional optical lithography techniques can not satisfy the resolution requirements (linewidths $< 1$ μm) we demanded while still maintaining uniform geometries along the line length. It is for this reason that we chose EBL techniques to construct the aluminum lines on top of the PMS. Since practical optical systems are ultimately limited in resolution by the wavelength of light, electron beams (or
Figure 4.1. Surface profile.

(a) Of an uncoated, diamond polished, sapphire substrate.
(b) Of polished sapphire coated to opacity with evaporated Al.
ion beams) present the only known means for fabricating submicron structures (Long 1981).

The major disadvantage of using EBL techniques is the proximity (scattering) effect in the resist layer due to both the forward scatter of the incident e-beam and the backscattered electrons from the PMS substrate. Resolution in the e-beam system is therefore limited by this proximity effect and not by the diffraction effects generated in traditional light optical systems (Varnell 1981).

Compensation for scattering is called "proximity effect correction" and can effectively improve geometry control, especially for geometries below one micron line widths. The extent of this proximity effect can be determined for particular resist/substrate layers by using Monte Carlo methods (Kyser 1981). The electron beam modulation necessary for writing a particular line geometry can then be calculated and automatically performed by interfacing the functions of the electron beam column (i.e., e-beam scan and beam current) to a computer. Because the SEM we used (ISI Super III - A) didn't have this type of e-beam modulation, our research was restricted to linewidths greater than one micron (i.e., in the 1.0 to 2.5 μm range) where the electron scattering effects are less noticeable. A complete discussion of the EBL techniques used for the ISI Super III-A is given in Appendix A.

The Electron Resist (PMMA) Exposure and Processing

PMMA (poly-methyl methacrylate) is a positive electron resist, developed by IBM Watson Research Center (Hatzakis 1969). It is
insensitive to visible light and is found to exhibit most of the properties desirable for high-resolution, electron beam exposure.

A schematic illustrating the fabrication of an Al line through a PMMA mask is shown in Figure 4.2. We now explain this process in more detail.

1) The PMMA is spin coated on to the surface of a nominally smooth aluminized mirror, at 2000 rpm for 40 seconds. This method yields measured coating thicknesses between 0.5 and 0.8 μm. The sample is then oven baked at 190°C for 1 hour after which it is ready for e-beam exposure (Figure 4.2a).

The charge density requirements for correct exposure of this PMMA layer lie between $5 \times 10^{-5}$ and $5 \times 10^{-4}$ Coulombs/cm² at 10-20 keV. At higher charge densities, cross-linking dominates to form over exposed resist that cannot be removed easily. For details of the e-beam exposure process, see Appendix A.

2) Developing away the exposed PMMA surface leaves the line depicted in Figure 4.2(b). Optimum resist exposure causes random scission of the molecular chains which effectively reduces the molecular weight of the polymer (Thornley 1965). Development is based on the molecular weight reduction, and it is accomplished by spraying the surface with a mixture of two liquids, one of which is a solvent and one of which is a nonsolvent of the original polymer (PMMA Developer).

Varying the developing time is another way to control the width of the resulting line. The more heavily exposed areas of the electron interaction volume in the resist are developed away first,
Figure 4.2. Fabrication of an aluminum line through a PMMA mask.
while the less exposed areas, or outer edges of the interaction volume, are removed only with longer developing time. Typical developing times have been between 10-60 seconds. This difference in developing time can cause as much as a factor of two difference in linewidth. Regardless of the necessary developing time needed, the final rinse (PMMA Rinse) is performed for 30 seconds. At this point consistency of the line width along the entire length of the line was checked using a Nanometric "Nanoline" Critical Dimension Computer System. Typically the linewidths in the PMMA layer can vary anywhere from 1 to 10% as a result of the proximity effect. However, linewidth variation of up to 100% or more can occur at the ends of the lines because of incomplete blanking of the e-beam as it is swept in a raster scan - line mode.

3) Once a satisfactory line has been written in the PMMA layer the remaining resist layer on the sample is flooded with "deep" UV light focused on the sample for a period of 900 seconds (Figure 4.2c). The UV source is a 1000 Watt, xenon doped, mercury lamp whose light has been filtered to emit radiation in the 180 to 250 nm range in order to expose the PMMA layer.

4) After UV exposure the sample is again coated by evaporation of aluminum as illustrated in Figure 4.2(d).

5) The remaining PMMA layer is now developed away along with the Al layer on top of it, leaving behind an Al line of height, h, width, w, and length, l, on the PMS (Figure 4.2(e)).

Since the rate of evaporation can be measured and controlled, and since the linewidth in the PMMA can be controlled by both the
exposure and developing time of the resist, both dimensions (i.e., height and width) of the resulting Al line can be made to predetermined specifications. However this is not easy to do. See Tables 4.1 and 4.2 for these results.

Several methods were used to determine the linewidths of the Al lines. The linewidths \( w \) listed as Width I in Table 4.1 were measured on a Nanometric "Nanoline" Critical Dimension Computer System. They are an average of 10 linewidth measurements from different points along the central portion of the line length. The uncertainties listed represent the standard deviation of these measurements. A calibration line standard was used to check the Nanoline calibration. We measured an average line width of \( 1.49 \pm 0.05 \) \( \mu \)m for this line. The actual width of the standard was reported by the manufacturer to be \( 1.0 \pm 0.2 \) \( \mu \)m. Therefore the Width I measurements are highly suspect and were only used to estimate relative differences between linewidths.

The line widths listed as Width II were measured using a moving reticle eyepiece on a Zeiss microscope at high magnification (Mag = 800 X). They are an average of several measurements from different points along the central portion of the line length. The uncertainties represent conservative estimates of how well this mechanical measurement could be performed. We believe that these values more closely represent the true linewidths.

The line heights \( h \) listed in Table 4.2 were measured on an "Alpha Step" sizing instrument. The Alpha Step is a mechanical sizing device which drags a diamond stylus across a surface to determine it's
Table 4.1. Measured widths ($w$) of the Al lines.

<table>
<thead>
<tr>
<th>Line</th>
<th>Width I ($\mu$m)</th>
<th>Width II ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4</td>
<td>1.28 ± 0.05</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>L1</td>
<td>1.37 ± 0.06</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>L3</td>
<td>1.31 ± 0.06</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>L2</td>
<td>1.44 ± 0.09</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>L2W</td>
<td>2.73 ± 0.03</td>
<td>2.3 ± 0.1</td>
</tr>
</tbody>
</table>

Table 4.2. Measured heights ($h$) of the Al lines.

<table>
<thead>
<tr>
<th>Line</th>
<th>Height ($\AA$)</th>
<th>Uncertainties ($\AA$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4</td>
<td>4600</td>
<td>± 460</td>
</tr>
<tr>
<td>L1</td>
<td>2800</td>
<td>± 280</td>
</tr>
<tr>
<td>L3</td>
<td>1700</td>
<td>± 170</td>
</tr>
<tr>
<td>L2</td>
<td>1000</td>
<td>± 100</td>
</tr>
<tr>
<td>L2W</td>
<td>1000</td>
<td>± 100</td>
</tr>
</tbody>
</table>
profile. Microscope slides were placed in the evaporator chamber along side the PMS's during the Al line fabrication process (Figure 4.1d). These slides therefore were coated to the same Al thickness as the line. The thickness of the Al deposition on these slides were measured and tabulated.

Measuring the deposition thickness of such a "soft" material as Al using a mechanical device like the Alpha Step is fraught with difficulties. Instead of rising smoothly up the Al step, the diamond stylus often "plows" into the Al, causing errors in the deposition thickness measurements. Our conservative estimates of the uncertainties in the values listed are about ± 10%. These uncertainties simply reflect the accuracy with which the step profile on the Alpha Step could be read.
CHAPTER 5

THE MEASUREMENTS

The Aluminum Mirrors

Differential interference contrast (DIC) photos of the mirrored surfaces used in this thesis are shown in Figures 5.1 and 5.2. Figure 5.1 shows the perfect mirrored surface (PMS) while Figure 5.2 is a typical section of a similar mirror taken after PMMA processing. These photos were taken on a Zeiss ICM 405 microscope and illustrate the degradation of the surface caused by the PMMA processing. Both surfaces produced interesting light scattering results that will be discussed in more detail in the next section.

All 16 Mueller matrix elements of the PMS photographed in Figure 5.1 were measured only for the case of "grazing incidence" ($\alpha = 11^\circ$); these are shown in Figure 5.3. The four unique matrix elements (i.e., $S_{11}$, $S_{12}$, $S_{33}$, and $S_{55}$) were also measured as a function of the angle of incidence, $\alpha$. For all samples the specific angles of incidence used were equal to grazing incidence, 22.5°, 45°, 67.5°, and near normal (≈ 81°) incidence. These curves appear in Figures 5.4, 5.5, and 5.6. The four unique matrix elements of the degraded mirror surface (DMS), photographed in Figure 5.2, were also measured for the case of grazing incidence only. These are shown in Figure 5.7 and will be compared with the results obtained from the PMS later. We will now discuss the various matrix elements separately.
Figure 5.1. The perfect mirror surface (PMS) at 1000 X's.
Bar line $\approx 10\ \mu m$.

Figure 5.2. The degraded mirror surface (DMS) at 1000 X's.
Bar line $\approx 10\ \mu m$. 
Figure 5.3. The entire Mueller matrix for the perfect mirror surface (PMS) at grazing incidence ($\alpha = 11^\circ$).
Figure 5.4. The matrix element curves for the perfect mirror surface (PMS) at near normal incidence ($\alpha \approx 81^\circ$).
Figure 5.5. The matrix element curves for the perfect mirror surface (PMS) at 45° incidence.
Figure 5.6. The matrix element curves for the perfect mirror surface (PMS) at grazing incidence ($\alpha = 11^\circ$).
Figure 5.7. The matrix element curves for the degraded mirror surface (DMS) at grazing incidence ($\alpha = 11^\circ$).
The $S_{41}$ or Total Intensity Matrix Elements

Special methods had to be used to measure any one of the four $S_{41}$ total intensity (TI) matrix elements. This was because the TI of the scattered light from these samples changed drastically from zero when the detector is positioned behind the sample to the maximum intensity of the specular peak at $\theta = \theta_s$. This caused the PMT current to vary abruptly by more than five orders of magnitude from $5 \times 10^{-14}$ Amp to $10^{-8}$ Amp at the specular peak. Since the PMT tube electronics could not respond "quickly enough" to this large intensity change at our scan rate, each of the TI curves were measured in two parts. First the detector was swept from $\theta = 0^\circ$ (behind the sample) to approximately $2.5^\circ$ before the specular peak and then stopped. Second the detector was swept from approximately $2.5^\circ$ after the specular peak to $\theta = 167^\circ$. The two resulting curves were then joined together by computer leaving a $5^\circ$ section of the $\theta$ scan centered around the reflected beam missing. This method was used to measure all TI matrix elements, $S_{41}$, at all angles of incidence, $\alpha$.

The Polarization Matrix Elements

The other twelve matrix elements were measured in the polarization (POL) mode, where the current of the PMT is servoed. A special circuit holds the current constant regardless of the TI at all angles. Polarization measurements can be taken over the full $\theta = 0^\circ$ to $167^\circ$ sweep which are only slightly perturbed by the abrupt intensity spike at the specular peak. As a further precaution, the intensity of the specularly reflected beam was reduced with NDF. The
polarization curves proceeded smoothly through this region, showing little effect of the large intensity of the reflected peak. Any spikes that do appear in the data are insignificant and have little effect on the curve and the resultant polarizations in this region.

Special methods had to be used to measure the twelve polarization matrix elements. We know that the surface of these mirrored samples contain naturally occurring microroughness as well as particulate contamination. Scattering from these defects creates a "random noise" added to the general polarization curve. Since these random features are unique to the particular area of the mirror being illuminated, we measured the signals from seven different positions on the mirror surface and averaged them by computer. This "smoothed out" the noise, leaving the general overall shape of the polarization curves. Data for all polarization matrix elements were averaged this way.

The Aluminum Lines and Degraded Mirror Surface (DMS)

Four Al lines were constructed (labeled L1, L2, L3, L4) on top of the PMS's. Each of the lines on these samples were constructed to have equal widths, but different line heights. See Tables 4.1 and 4.2 for specific line dimensions. DIC photos of a typical line and DMS are shown in Figures 5.8 to 5.10. Figure 5.8 shows the approximate area that the laser illuminates the sample, while Figure 5.9 shows the line profile at higher magnification. Figure 5.10 shows the bulbing end of the line of Sample L4. This is an artifact caused by incomplete beam blanking at the end of the SEM raster scan during e-beam exposure of
Figure 5.8. Sample L4 taken at 200 X's.

Bar line = 100 μm. Upper: dark field illumination. Lower: yellow (DIC) illumination.
Figure 5.9. Sample L4 taken at 1000 X's.
Bar line $\approx 10 \, \mu m$.

Figure 5.10. Bulbing end of sample L4 taken at 1000 X's.
Bar line $\approx 10 \, \mu m$. 
the PMMA mask layer. In order to ensure that the portion of the line illuminated by the laser be as uniform in width as possible, the line length was deliberately made approximately three times longer than the laser beam diameter. For scattering studies, these samples were then illuminated near line center, thereby avoiding the ends of the line completely.

Figure 5.11 shows an SEM micrograph of the line of Sample L4. The line shape in cross section is essentially a rectangle with slightly rounded corners.

Figure 5.12 displays the complete 16 element Mueller matrix for Sample L4 obtained at grazing incidence. These curves show again that the only unique matrix elements are $S_{11}$, $S_{12}$, $S_{33}$, and $S_{44}$. All four line samples (i.e., L4, L3, L2, L1) were measured as a function of the same angles of incidence, $\alpha$, used for the mirror samples in the previous section. We will refer to this group of measurements as a rotational-height study, since lines of equal width but different heights were investigated as a function of the same incident angle, $\alpha$.

Figures 5.13-5.15 show some of the data obtained in the rotational study of Sample L4. Rather than displaying all the data that resulted from these measurements, plots were made to illustrate the phase shifts of the peaks in the polarization curves that occur as the line height changes. They are shown in Figures 5.16 and 5.17. It suffices to show only a few examples because the overall trends exhibited in these curves persist for all matrix elements, at all angles of incidence. The interpretation of these data will be discussed in the following sections.
Figure 5.11. SEM micrographs of Sample L4 taken at 17K X's.
Bar line $= 1 \, \mu m$. 
Figure 5.12. The entire Mueller matrix for Sample L4 (height ≈ 4600Å, width ≈ 1.1 μm) at grazing incidence (α ≈ 11°).
Figure 5.13. The matrix element curves for Sample L4 (height ≈ 4600Å, width ≈ 1.1 μm) at grazing incidence (α ≈ 81°).
Figure 5.14. The matrix element curves for Sample L4 (height ≈ 4600Å, width ≈ 1.1 μm) at 45° incidence.
Figure 5.15. The matrix element curves for Sample L4 (height = 4600Å, width = 1.1 μm) at grazing incidence (α = 11°).
Figure 5.16. Rotational-height study plots of the $S_{33}$ matrix element maxima at grazing incidence ($\alpha = 11^\circ$) for three sample heights.
Figure 5.17. Rotational-height study plots of the $S_{33}$ matrix element maxima at grazing incidence ($\alpha = 11^\circ$) for Sample L3 (height = 1700Å) and sample L2 (height = 1000Å).
In order to further investigate the relative importance of height and width we constructed another line (Sample L2W) which has the same height as Sample L2 but is slightly larger than twice the width. Figures 5.18 and 5.19 show the four unique matrix elements obtained at grazing incidence for these samples (L2 and L2W). Interpretation of these curves will also be discussed in detail in the following sections.

Figures 5.20-5.23 show the S_{11}, total intensity curves obtained from Samples L4, L3, L2, and L2W illuminated at grazing incidence. A more detailed analysis and comparison of these curves with the theoretically predicted intensity distributions from a single slit diffraction grating will be given later.

The S_{11} or Total Intensity Matrix Elements

The TI curves for these lines were measured in the same way as the TI curves of the mirrors. The measuring techniques used to obtain these four total intensity matrix elements are discussed in the first page of this chapter.

The Polarization Matrix Elements

Data for the twelve polarization matrix elements from the line/mirror samples did not need to be averaged as did the mirror samples of the previous section. The lines constructed on these mirrors are very effective scatterers. Since they scatter much more light than the surface microroughness, the polarization curves are dominated more by the line than by the surface. The spikes that appear in the curves at the reflection angle can be ignored as before.
Figure 5.18. The matrix element curves for Sample L2 (height = 1000Å, width = 1.0 μm) at grazing incidence (α = 11°).
Figure 5.19. The matrix element curves for Sample L2W (height $\approx 1000\lambda$, width $\approx 2.3$ $\mu$m) at grazing incidence ($\alpha \approx 11^\circ$).
Figure 5.20. The $S_{11}$ total intensity curve for Sample L4 (height = 4600Å, width = 1.1 µm) at grazing incidence ($\alpha = 11^\circ$).
Figure 5.21. The $S_{11}$, total intensity, curve for Sample L3 (height $\approx 1700\lambda$, width $\approx 1.0$ $\mu$m) at grazing incidence ($\alpha \approx 11^\circ$).
Figure 5.22. The $S_{11}$, total intensity, curve for sample L2 (height $\approx 1000\,\text{Å}$, width $\approx 1.0\,\text{µm}$) at grazing incidence ($\alpha \approx 11^\circ$).
Figure 5.23. The $S_{11}$, total intensity, curve for sample L2W (height $\approx 1000\,\text{Å}$, width $\approx 2.3\,\mu\text{m}$) at grazing incidence ($\alpha \approx 11^\circ$).
since the shape of the polarization curves have been shown to be smooth in these regions.
CHAPTER 6

DISCUSSION

The discussion and interpretation of the experimental results are organized into two main sections: 1) the aluminum mirrors and 2) the aluminum lines on the mirrors.

The Aluminum Mirrors

The Perfect Mirror

The main goal of our research was to experimentally determine the 16 element Mueller scattering matrix for a perfect mirrored surface. The first question to arise is: what do we mean by scattering from a perfect mirrored surface? A truly perfect mirrored surface (PMS) should not scatter at all! All we would get are the results predicted for the ideal Fresnel mirror, discussed earlier. No PMS exist in the ideal sense of the word perfect, only mirrored surfaces which approach the ideal Fresnel mirror. For our studies we produced a surface as close to an ideal Fresnel mirror as possible. Great care had to be taken to obtain quality mirror samples. In fact this turned out to be the most time consuming and painstaking aspect of our research. Our reasons for choosing Al for our mirror work and the details involved to produce the Al mirrors are given in Chapter 4. Because the PMS is not an ideal Fresnel mirror, we had to be able to characterize the mirror and describe its imperfections.
One method we used was Differential Interference Contrast (DIC) microscopy to photograph the PMS. By illumination with different wavelengths (or colors) we could very effectively observe and photograph even the smallest defects (pits, scratches, etc.) on the mirror surface. Figure 5.1 is a DIC photo of the PMS. This photo, taken at 1000X under yellow light illumination, clearly shows the pinholes in the PMS.

Another method we used was polarized light scattering nephelometry to measure the 16 element Mueller matrix. We first measured all 16 $S_{ij}$'s of the PMS shown in Figure 5.1 for the special case where the PMS was illuminated at grazing incidence. The 16 element Mueller matrix is shown in Figure 5.3. These Mueller matrix elements represent the complete set of light scattering data. It contains all of the polarized light scattering information obtainable from this scattering system at this wavelength. In this respect, the Mueller matrix represents a unique "fingerprint," completely characterizing any scattering system. This is the first experimentally measured Mueller matrix for a PMS.

From these curves we can see that not all of the matrix elements are unique. This is generally true of scattering systems where sufficient symmetry exists, i.e., spheres, cylinders, etc. Some of the matrix elements are zero (i.e., $S_{12}, S_{44}, S_{22}, S_{24}$), some are identical (i.e., $S_{12} = S_{24} = S_{12}$; $S_{11} = S_{31} = S_{31}$), some are inverses (i.e., $S_{24} = -S_{44}$), and some are combinations of matrix elements (i.e., $S_{24} = S_{11} + S_{12}$). Note: The $S_{22}$ matrix element is equal to $S_{11}$ only when scattering is from spherical particles. Differences between $S_{11}$
and \( S_{22} \) are measures of the deviation from sphericity. For cylinders, and in our case of lines on a surface, \( S_{22} \) has a constant value of +100% for all angles. It is recommended that \( S_{22} \) be investigated initially along with the others until its behavior is understood. Therefore, the only unique matrix elements for the PMS are the \( S_{11} \), \( S_{12} \), \( S_{22} \), and \( S_{33} \). Although the data presented here (Figure 5.3) is only for grazing incidence, this uniqueness holds for all incident angles.

The four unique matrix elements from the PMS for several different angles of illumination are shown in Figures 5.4-5.6. They show the additional phase information that develops as the sample is rotated in the incident laser beam. The matrix elements are a measure of the efficiency with which a scatterer converts one polarization state into another (see Figure 3.3 for the polarization conversion schemes). This sample rotation study shows how the polarization conversion efficiencies (i.e., the \( S_{ij} \)'s) vary with the illumination angle, \( \alpha \).

The Degraded Mirror

The next scattering system we wanted to study was the perfect Al line on top of the PMS. Electron beam lithography (EBL) techniques were chosen to construct this line since EBL methods yield the highest resolution for the line dimensions (linewidths \( \approx 1 \) \( \mu \)m) we wanted. However all lithography techniques require the application and removal of different chemicals and resist layers to the PMS. (For a complete description of the PMMA resist application, exposure, processing, and
removal see Chapter 4.) This chemical processing causes additional
degradation to the PMS. After this processing of the PMS we end up
with a degraded mirror surface—hereafter called a DMS. Figure 5.2,
a DIC photo of a degraded mirror surface taken at 1000X under yellow
illumination shows how the PMS was degraded by the PMMA processing.
This clearly shows that the number of pinholes on the DMS is much
larger than on the PMS shown in Figure 5.1.

The scattering information obtained from these DMS's are just
as important and interesting as the results obtained from the PMS. We
therefore decided to include them as an additional topic in this
thesis. Figure 5.7 shows the 4 unique matrix elements from the DMS
photographed in Figure 5.2 for the special case of $\alpha = $ grazing
incidence. The features of the 16 element Mueller matrix for the DMS
are the same as for the PMS discussed earlier. There are only 4
unique matrix elements ($S_{11}, S_{12}, S_{13}, S_{14}$) for all angles of
illumination.

Comparisons and Contrasts

Comparison of the 4 unique matrix elements from the PMS
(Figure 5.6) for the case of grazing incidence with the 4 unique matrix
elements from the DMS (Figure 5.7) reveal several interesting
features:

1) The $S_{11}$ (TI) signal from the DMS is approximately an order
of magnitude larger than the $S_{11}$ signal from the PMS at all
scattering angles, $\theta$.  

2) The $S_{11}^{(POL)}$ signal from the DMS is similar in shape to that of the PMS; however, polarization can be as much as 40% higher at some scattering angles (i.e., around $\theta = 90^\circ$).

3) The $S_{11}^{(POL)}$ and $S_{22}^{(POL)}$ signals from the perfect and degraded mirror surfaces are almost identical.

We now try to reconcile the light scattering ($S_{ij}$) data with the photographic data. The photographs in Figures 5.1 and 5.2 show that the number density of the surface defects on the DMS is about 5 times larger than the PMS. These surface defects are "pinholes" in the aluminum mirrors, ranging in size from 0.2 to 1.0 $\mu$m in diameter. The pinholes on the PMS are artifacts left in the aluminum film caused by residual particulates on the sapphire substrates. These particulates could not be removed by the methods used to clean the substrates before evaporation. The PMS degraded even further with the application and removal of the PMMA coating used to construct the Al lines. The increased number of imperfections increased the scattering since scattering is proportional to the defect number density.

The change in the $S_{11}^{(POL)}$ signal from the DMS is attributed to an additional increase in the size and/or shape of the surface defects. It is not affected by the number density since the normalized polarization curves are independent of the number density of scatterers in a system. Consider for example the case of single scattering from monodispersed spheres in solution. Adding or subtracting spheres from this scattering system will change only the TI, not the normalized polarization measurements. Therefore, the $S_{11}^{(POL)}$
(TI) signal carries information about both the size and number density of the surface defects while the $S_{12}$ polarization signal is extremely sensitive to the small size and/or structural changes of the surface defects. The other two unique matrix elements, $S_{23}$ and $S_{13}$, do not seem to be as strongly affected by the structural changes occurring on these surfaces. However they are probably not totally insensitive to the structural changes of surfaces in general.

**The Aluminum Lines on the Mirrors**

We decided to use EBL techniques to fabricate the Al lines on top of the PMS's. The chemical processing necessary for EBL work unavoidably results in additional degradation of the PMS. All PMS on which Al lines were written experienced identical degradation. It is regrettable that the Al lines could not be constructed on the PMS without degrading the surface. Such a surface would be a more "fundamental" surface, i.e., a surface more closely resembling an ideal Fresnel mirror, to be measured as a background to the Al lines. Fortunately the degradation of the PMS did not complicate the interpretation of the scattering data from the Al lines, because the "masking" effects of the DMS did not significantly influence scattering from the Al line. Although the Al line and the DMS act as non-independent scatterers "masking corrections" may be used effectively since the DMS scatter is very much smaller than the scattering from the Al lines themselves.
Sample L4

DIC photos of Sample L4 appear in Figure 5.8 showing the approximate area of illumination of the sample. Only a central portion (length ≈ 0.7 μm) of the total line length (l = 2.5 mm) was illuminated with the laser. The central section is therefore far from the broadened ends of the lines. This broadening is clearly seen in Figure 5.10 which shows the line end of Sample L4. The DIC photos in Figures 5.8 and 5.9 show the shape or profile of L4 to be extremely uniform; however, the exact geometrical shape of L4 is shown clearly in the SEM micrographs of Figure 5.11. Even under high SEM magnification its height (h) and width (w) appear to be extremely uniform but with some small curvature along its length (l). Furthermore these micrographs show that the line shape in cross section is essentially a rectangle with slightly rounded corners. Additional artifacts left during the deposition of the Al line appear as small bumps on top of the line.

The entire 16 element Mueller matrix from this sample is presented in Figure 5.12. It was measured for the special case where the sample was illuminated at grazing incidence. There are again only 4 unique matrix elements at all illumination angles, α. As was the case with the PMS and DMS, only the 4 unique matrix elements were measured as a function of the angle of illumination.

There appear to be no "magic" angles for any of the surfaces studied, i.e., angles where special features would be enhanced or subdued. All of the surfaces studied (PMS, DMS, and line-mirror samples) were illuminated at the five following angles: grazing
incidence ($\alpha = 11^\circ$), $22.5^\circ$, $45^\circ$, $67.5^\circ$, and near normal incidence ($\alpha = 81^\circ$).

The grazing incidence angle $\alpha = 11^\circ$ gives information over the largest angular region, i.e., $\theta = 22^\circ$ to $\theta = 167^\circ$. The minimum $\alpha$ we could get was dictated by the size of the laser beam projection on the surface of the mirrors (length of unobstructed mirror surface $< 0.5^\circ$).

Near normal incidence ($\alpha = 81^\circ$) gets data that fits simplified theoretical calculations, such as the single slit diffraction formula. It is also the opposite extreme of grazing incidence. The other incident angles were chosen for the following reasons: $\alpha = 45^\circ$ puts the reflected beam half way between the $\theta = 0^\circ$ to $\theta = 180^\circ$ scan, i.e., at $\theta = 90^\circ$; $\alpha = 22.5^\circ$ and $\alpha = 67.5^\circ$ are complementary angles in the $\theta = 0^\circ$ to $\theta = 180^\circ$ scan. Their reflected beams appear at $45^\circ$ and $135^\circ$, respectively.

Some of the data from the $\alpha$-dependent rotational study of Sample L4 appear in Figures 5.13-5.15. We now comment on the results of this rotational study.

The $S_{11}$ or total intensity (TI) curves. The total intensity $S_{11}$ curves, especially those taken at grazing incidence, closely resemble single slit diffraction patterns. (Note: The $S_{11}$ curves are plotted on a log scale.) In order to get a better fit and relate the data to the scatter from just the Al line alone, the intensity due to the DMS has to be subtracted out. When this is done the curves still don't match. One main difference is that the theoretically predicted intensity distribution for the single slit goes to zero at some angles while the corrected $S_{11}$ curves never do. Further discussion along
with more quantitative information about the measured TI curves will be given in a later section.

The \( S_{12}, S_{21}, \) and \( S_{33} \) (POL) curves. All of these polarization curves, especially those taken at grazing incidence, show extensive phase information. One feature to notice about these curves is that phase shifts occur but the number of peaks remain almost constant for all the different angles of illumination. Before we can say much more about these curves the POL measurements must be related to just the Al line. In this case however simple subtraction of the DMS polarization curves isn't valid. We have to take into account both the intensity and the polarization of both components. The details of this procedure are discussed in the next section.

Normalization of Polarization Curves in Multi-Component Systems

We measured the scattering matrix for the DMS so we could use that information to correct the POL matrix elements for the Al lines. The data from the Al lines, as it is presented in this thesis, is a mixture of the light scattered from the DMS's and the Al lines themselves. The effect of two or more scattering systems competing with each other is referred to as masking of one scatterer or scattering system by another (Bickel, Yousif, and Bailey 1984). In this case, the scattered signal from the Al line will be partially masked out by the scatter from the DMS. For the total intensity case \( (S_{11}) \) the TI signal from the background mirror can be directly subtracted from the measured TI signal to obtain the true signal for just the Al line. However, this simple subtraction doesn't work for
the polarization signals because the POL measurements have been normalized by the TI at every angle, \( \theta \). In other words the polarization from the two combined scatterers is not simply the sum of the two individual polarizations but depends on what intensity a particular polarization resides on. The polarization of the system that scatters more light will dominate the polarization of the mixture. For the two component system of DMS, M, and line, L, we can write

\[
\pi_M = \frac{I_M^P - I_M^S}{I_M^P + I_M^S} \quad \pi_L = \frac{I_L^P - I_L^S}{I_L^P + I_L^S}
\]

where \( \pi \) = the fractional polarization, \( I \) = the measured intensity; and \( p_s \) = the parallel and perpendicular components, respectively. Therefore for the fractional polarization of the line plus the DMS we get

\[
\pi(L) = \frac{(I_M^P - I_M^S) + (I_L^P - I_L^S)}{(I_M^P + I_M^S) + (I_L^P + I_L^S)} = \frac{\pi_M(I_M^P + I_M^S) + \pi_L(I_L^P + I_L^S)}{I_M^T + I_L^T}
\]

\[
= \frac{\pi_M I_M}{I_L}. \quad (6.1)
\]

A numerical example showing how this correction is applied to our data can be performed using Figures 6.1 and 6.2. Figure 6.1 shows the TI curve for the DMS and the TI curve for the combination of the A1 line.
Figure 6.1. The $S_{11}$, total intensity, curves for Sample L1 and the degraded mirror surface (DMS) at grazing incidence ($\alpha = 11^\circ$).

Figure 6.2. The $S_{33}$, polarization, curves for Sample L1 and the degraded mirror surface (DMS) at grazing incidence ($\alpha = 11^\circ$).
plus DMS from Sample L1, at grazing incidence. This figure shows that at $\theta = 112^\circ$ the T1 of the combined scatterers (i.e., line plus mirror) is 100 times greater than the T1 from the DMS alone. Therefore, $(100) \times I_M^T = I_L^T$.

Figure 6.2 shows the matrix elements for the DMS and the line plus the DMS of Sample L1, at grazing incidence. This figure shows that at $112^\circ$

$$\pi_M = -0.25 \quad \pi(\xi) = 0.4$$

Using these values in Eq. (6.1) we get

$$\pi(\xi) = 0.4 = \frac{-0.25(I_M^T + \pi_L(I_L^T))}{I_M^T + I_L^T} = \frac{-0.25(I_M^T + \pi_l(100I_M))}{I_M^T + 100I_M}$$

$$= \frac{(-0.25 + 100\pi_L^T)I_M}{101 I_M^T}.$$

Solving for $\pi_L$ gives

$$\pi_L = 0.4065 = 40.65\%$$

i.e., the additional scattering due to the DMS was small and has affected the 40% polarization signal at $112^\circ$ by only 0.65% in this case. Using total intensity and polarization data, this kind of "normalization" can be done for all scattering angles, $\theta$, to extract
the polarization matrix elements of the isolated Al line from our data. We did not pursue this any further since all of the quantitative measurements obtained in this thesis were determined from the Ti, $S_{11}$, signals.

More Aluminum Lines

The 4 unique matrix elements were measured as a function of the illumination angle, $\alpha$, for all line-mirror samples (L4, L3, L2, L2W, L1). All samples were illuminated at the same angles with respect to the incident laser beam by rotating them in the beam from grazing to near normal incidence. The four matrix elements obtained from a "rotational study" of Sample L4 are shown in Figures 5.13-5.15. Similar data was taken for all the line-mirror samples. The lines on these samples were constructed with heights ranging between 4600 Å (Sample L4, $h = \text{one wavelength} = 4416$ Å) and 1000 Å (Sample L2, $h = \frac{1}{4} \text{wavelength}$), with several intermediate heights. (See Tables 4.1 and 4.2 for exact line dimensions.) This study was performed to see how sensitive the matrix elements are to line-height variations and different illumination angles. Since all of the data from this rotational-height study showed the same trends, plots shown in Figures 5.16 and 5.17 were made to illustrate the basic results of this study. These results can be summarized as follows:

1) Figures 5.16 is a plot of the angular position, $\theta'$, of the peaks in the S33 matrix element measured with respect to the angular position of the specular peak, $\theta_{sp} = 0^\circ$. These data are from the Samples L4, L1, and L3 illuminated at grazing incidence ($\alpha = 11^\circ$).
This plot shows that for any given illumination angle the maxima of all the matrix elements spread out, or shift phase, as the line height decreases. The largest spacings occur for the smallest line height (Sample L3, h = 1700 Å). Identical behavior was observed at all angles of illumination, θ, in all four matrix elements from these samples. What is very surprising about this is that new maxima rarely occur in spite of the fact that the samples vary by more than a factor of two in line height. Changing the line height has very little effect on the phase shifts in any of the matrix elements regardless of the angle of illumination.

2) Figure 5.17 shows the phase shifts of the peaks in the $S_{11}$ matrix element for Samples L3 and L2, illuminated at grazing incidence. Samples L3 and L2 have nearly identical line widths with line heights approximately equal to 1700 Å and 1000 Å respectively. The plots of phase shifts resulting from these two samples are seen to overlap and sometimes criss-cross. This was true for all matrix elements and all angles of illumination. From this observation it seems that none of the matrix elements are useful in differentiating between changes in line-height below 2000 Å, regardless of the angle of illumination of the samples.

Now we show what happens when we keep the height of the lines the same and change the widths. Figures 5.18 and 5.19 are plots of the 4 unique matrix elements from Samples L2 and L2W, again for illumination at grazing incidence. Both of these samples have identical line heights, h = 1000 Å; however, the width of these samples differ by roughly a factor of two. The respective widths of
samples L2 and L2W are approximately 1.0 μm and 2.3 μm. Now the total number of peaks has increased, causing the angular separation of the peaks to decrease by roughly a factor of two for Sample L2W. This factor of two corresponds exactly to the increased width of Sample L2W over Sample L2. This behavior was observed in all matrix elements, for all angles of illumination of these two samples.

From these data we see dramatic evidence that the scattering is very dependent on the line widths. In other words, changing the line width by a factor of two caused a drastic change in both the total number of peaks as well as the phase in the matrix element peaks. However, changing the line height by a factor of two caused only small changes in the position of the peaks and little change in the total number of peaks.

Single Slit Diffraction from an Aluminum Line

We compared these results with a simple geometrical model, i.e., that of diffraction by a single slit illuminated at various angles, α. Consider the ray diagram in Figure 6.3. If we assume low scatter from the DMS, i.e., σ << λ, rays A and G (and all others striking the mirror) will simply be specularly reflected and never reach the detector at point P. Now examine the two different geometric cases concerning line height and line width separately.

**Case 1.** The line geometry is: a) a rectangle of height, h, width, w, or b) a rectangle of height, h + Δh, width, w. For both situations a) and b) the diagram shows that the same amount of scattered light from the top surface of the rectangles will reach the
Figure 6.3. Ray diagram showing the reflected and diffracted rays from the aluminum line/mirror surface.
detector at point P. The only difference between the two situations will be that ray B for geometry lb will be scattered by the edge of the rectangle and end up at point P, while for geometry la it would simply be specularly reflected.

Case 2. The line geometry is: a) a rectangle of height, h, width, w, or b) a rectangle of height, h, width, w + Aw. For both situations a) and b) we can see from the diagram that the same amount of scattered light from the edge of the rectangle will reach the detector at point P. The only difference here between the two situations a) and b) is that much more scattered light will reach the detector as Aw increases.

Since both of the geometries depicted in Case 1 and 2 have equal sections of edge length illuminated, the amount of scattered light reaching the detector will be the same in both cases. With this in mind we can make one more simplification of the problem and neglect the contribution to the scattered light from the edges, since it is equal in both cases. With this assumption we have to consider only the scattered light from the top surface of the lines. When we do this we get the geometrical situation for the ideal diffraction grating with one groove described earlier in the introduction. (Note: We discussed an extremely idealized situation in an attempt to treat the phase (interference) part of this complex scattering problem with simple ray tracing (geometrical) methods. The complete E & M boundary value problem must be solved and recast into the matrix formulation in order to predict all of the POL measurements obtained from these samples.)
The only quantitative information we can get from this highly idealized treatment is that the intensity distribution for diffraction from a single slit, matches our $S_{11}$, $T_1$, matrix element, in some cases. Figures 6.4 and 6.5 show the theoretical intensity distribution for single slit diffraction from slits whose widths are 1.25 $\mu$m and 2.3 $\mu$m. (Note: These intensity distributions are plotted on a log scale). Both of these plots were made for the special case where the slits were illuminated at grazing incidence, i.e., for $\alpha = 11^\circ$ in Eq. (1.1). Comparing these plots with the $S_{11}$ plots shown in Figures 5.20-5.23 we notice several things:

1) There is an exact correspondence between the theory maxima, i.e., intensity maxima for slit widths equal to 1.25 $\mu$m and 2.3 $\mu$m, and the maxima appearing in the $S_{11}$ curves for Samples L2 and L2W, respectively.

2) The values used for the slit widths in these calculations do not fall within the uncertainties of the measured widths of Samples L2 and L2W. See Table 4.1 for measured line widths and uncertainties.

3) If the $S_{11}$ curves for the DMS are subtracted out of the $S_{11}$ curves for Samples L2 and L2W, the minima approach (but never correspond exactly to) the minima of single slit theory.

4) The $S_{11}$ curves for Samples L4 and L3 do not match single slit diffraction theory at all.

These data show that the samples with only the smallest height lines, i.e., L2 and L2W; $h = 1000$ Å, have $S_{11}$, $T_1$, curves that fit single slit diffraction theory. We see here dramatic evidence that...
Figure 6.4. Theoretical intensity distribution for diffraction from a single slit of width = 1.25 µm, illuminated at grazing incidence (α = 11°).
Figure 6.5. Theoretical intensity distribution for diffraction from a single slit of width = 2.3 μm, illuminated at grazing incidence (α = 11°).
simple ray tracing methods can be used effectively only for small line heights. Larger line heights result in additional scattering which cannot be theoretically accounted for by geometrical methods. Therefore, the exact phase structure in the $S_{11}$ curves for samples with larger line heights can be predicted only by solving the complete E & M boundary value problem.
CHAPTER 7

CONCLUSION

Many techniques and instruments are currently used to characterize surfaces. In addition to the traditional methods used to characterize mirrored surfaces, we used polarized light scattering nephelometry. The experimentally determined 16 element Mueller matrix contains all of the polarized light scattering information obtainable from any scattering system. It can therefore be used as a powerful tool in experimental surface science research. This thesis presented the first experimentally measured Mueller matrix for a perfect mirror surface. Comparison of these results with the Mueller matrix for a degraded mirror surface showed which of the matrix elements were most sensitive to surface degradation.

In addition to the study of such mirrors, we investigated the scattering from a thin aluminum line (width = 1.1 μm) fabricated on top of the PMS. Since the line presents additional geometric possibilities, we studied the line as a function of illumination angle, α, as well as a function of its width and height. These data are from highly characterized systems and therefore worthy of serious theoretical attention. Until theories are developed, most of the information obtainable from these light scattering techniques will be qualitative. For example, the scattering from these lines has been shown to be a strong function of line width and not line height. The
exact functional dependence has not been determined in this work and no theory yet predicts what it should be.

Quantitatively, we found that simple diffraction theory can be used to predict the maximum - minimum locations on the $S_{11}$, total intensity, curves from lines whose heights are $\leq 1000$ Å. For line heights above this single slit diffraction theory does not work. Complete theoretical treatment of this scattering problem must be done before the $S_{11}$ and the other polarization matrix elements from larger lines can be predicted.

Many instruments, such as the Nanoline, Alpha Step, analytical microscopy, etc., using both optical and mechanical techniques are available to measure line sizes. However, none of these instruments are very accurate when the line dimensions are of the order of 1 μm or less. Surface structures of this size are rapidly becoming commonplace in many areas of technology, especially in the microcircuit industry. We believe that polar nephelometry can make more accurate measurements in this range than some of the other techniques available. However more experimental as well as theoretical research is needed before this can happen.

Generally, we have found it advantageous to study light scattering from complex systems using very systematic procedures. This research was conducted with that in mind. Highly characterized systems, like the perfect mirror surface and the aluminum line samples, were studied first. When scattering from these highly idealized systems is well understood, they can be gradually degraded
and studied in order to understand the complex scattering systems that exist in the "real world."
APPENDIX A

EBL TECHNIQUES ON THE SEM

In order to obtain the highest resolution and most uniform geometries for lines written with the SEM, several of the operating parameters of the ISI Super III-A SEM had to be considered and experimentally determined (Goldstein et al. 1981).

The working distance (WD) on the SEM results in a trade off between resolution (short WD) and depth of field (large WD). Since we want the beam divergence to be as small as possible through the resist layer, we need a large WD, or depth of field.

There is also a trade off between spot size and beam current. To obtain the smallest linewidths possible it was necessary to work at the minimum spot size and compensate for the loss in beam current by increased exposure times.

The magnification on the SEM is given by \( M = \frac{L}{l} \) where \( L \) = the constant length of the CRT scan and \( l \) = the length of the e-beam scan on the sample. Therefore, knowing the magnification (which can be read off the display on the scope) and the length of the CRT scan, we can make a good estimate of the length of the line being written.

The fact that PMMA is reactive to incident e-beam energies between 10-20 keV, restricts us to using the middle HV setting of the SEM at 18.5 keV. The other available settings are well out of range.
By trial and error the following SEM settings on the ISI Super III - A were found to give the most uniform linewidths within the range of interest for our experiments.

**SEM Settings:**
- HV = middle = 18.5 keV
- WD = 30 mm
- Spot Size = Min.
- Tilt = 0 deg.
- Dynamic Focus = 0
- Mag = 70 X
- Sweep = Line mode (Rapid)
- Exposure Time = 10 - 15 minutes

**Procedure:** The PMS, coated with PMMA, is mounted on an aluminum stud and grounded using conductive paint. Saturation of the filament is performed and an edge of the surface is imaged and brought to focus in the TV mode as rapidly as possible (stigmatism is performed if necessary). Then using the settings listed above, in the spot mode, the e-beam is moved using the X-Y translators to the center of the sample. The line mode is then activated and the sweep continued for approximately 10-15 minutes.

As an example, the following calculation could be used to determine a "ball park" estimate of the exposure time needed to produce a particular line geometry.

At settings of WD = 30 mm, HV = Middle, Spot Size = Min it was found that the Faraday cup measurement of the incident beam current was

\[ I_b = 1.9 \times 10^{-12} \text{ Amp} = 1.9 \times 10^{-12} \text{ C/sec} . \]

Since the necessary charge density for PMMA exposure must fall
between $5 \times 10^{-3}$ and $5 \times 10^{-4}$ C/cm$^2$, we can calculate the exposure time, t, using the parameters selected to generate the line in Figure 5.8, i.e., length $= 2.5$ mm, width $= 1.1$ um. Therefore

\[
\text{Charge Density} = \frac{1.9 \times 10^{-12} \text{ C/sec} \times (t)}{1.1 \times 10^{-4} \text{ cm} \times 0.25 \text{ cm}} = 5.0 \times 10^{-3} \text{ C/cm}^2.
\]

Solving for t in this equation gives $t = 720$ sec. Therefore the correct exposure times are of the order of 12 minutes for this geometry and beam current.
REFERENCES


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