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**PHASE SHIFTING INTERFEROMETRIC
IMAGING ELLIPSOMETER**

**By
Conrad Wells**

**A Dissertation Submitted to the Faculty of the
COMMITTEE ON OPTICAL SCIENCES (GRADUATE)**

**In Partial Fulfillment of the Requirements
For the Degree of**

DOCTOR OF PHILOSOPHY

In The Graduate College

THE UNIVERSITY OF ARIZONA

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requirement for the Degree of Doctor of Philosophy

James C. Wyant
James C. Wyant

5/14/99
Date

Jack D. Gaskill
Jack D. Gaskill

5/14/99
Date

William J. Dallas
William J. Dallas

5/14/99
Date

Date

Date

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James C. Wyant
Dissertation Director

James C. Wyant

6/25/99
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ABSTRACT

A novel imaging ellipsometer has been developed; the phase shifting interferometric imaging ellipsometer (PSIIE) is the first ellipsometer to use phase-shifting interferometry for data acquisition. The only moving part in the system is a solid state PZT. The PSIIE uses a polarization interferometer, followed by a Wollaston prism, to obtain simultaneously, samples of the S and P polarization component interferograms. Interferogram phase yields the ellipsometric parameter, Δ , while the fringe modulation yields the tangent of the ellipsometric parameter Ψ . The instrument can perform multiple wavelength and multiple angle-of-incidence ellipsometry over the entire visible range with the addition of a tunable laser source. Repeatability of the prototype instrument approaches 0.15° for the measurement of Δ , and 0.4° for Ψ . Absolute accuracies are 1° for Δ and Ψ . Calculations indicate that hardware and software improvements would achieve a precision and absolute accuracy below 0.1° .

INTRODUCTION

The impetus for the development of the phase shifting interferometric imaging ellipsometer can be found in the applications of interference microscopy. Interference microscopes measure the difference in phase between a reference wave and a wave reflected from a surface under test. Surface height variations are encoded into the phase of the reflected wave and are determined via the measurement of the phase difference between the two beams. Consequently, any variations in the phase change on reflection across a sample will cause errors. An imaging ellipsometer, in conjunction with an interferometric profiler could remedy these phase errors.

Interference microscopes have limitations when investigating surfaces that contain two or more “dissimilar materials”. Variations in the phase change on reflection cause errors in the characterization of the surface profile. Magnetic recording heads used in modern hard disk drives, and dielectric or metal-coated silicon wafers, are examples of dissimilar material applications in interferometric profiling.

When light is reflected, the phase of the electric field is altered. The phase change on reflection is a function of the optical properties of the material and the thickness of any thin-films, if present. If the sample being measured is composed of a single uniform material, the phase change on reflection is constant across the sample and does not corrupt an interferometric measurement. On the other hand, if dissimilar materials are

present, there are two contributions to the measured phase. The first is the desired phase due to the surface profile; the second is the variation in the phase change caused by the dissimilar materials. The measured phase is the sum of these two phases. In order to measure the sample using standard interferometric techniques, the sample would have to be coated with a metallic layer to remove the phase change effects. This usually destroys the sample.

The phase change on reflection can be calculated as a function of position from ellipsometric data and removed from the interferometric data, yielding the desired surface profile. An interferometric profiler, in conjunction with an imaging ellipsometer, could measure dissimilar material samples that are currently not measurable.

The long-term goal of this work was the development of a prototype imaging ellipsometer to address the measurement of magnetic recording heads.

DEVELOPMENT OF THE PHASE SHIFTING INTERFEROMETRIC ELLIPSOMETER

Ellipsometers measure the change in the state of polarization following reflection from a surface. This involves the measurement of two quantities. The first ellipsometric parameter, Δ , is defined as the phase difference between the P and S phase changes on reflection. The second parameter, Ψ , is the inverse tangent of the ratio of the amplitude reflection coefficient of the P and S polarizations. They can be represented by the following equation:

$$\rho = \frac{\rho_p}{\rho_s} = \frac{|\rho_p|}{|\rho_s|} e^{i(\Phi_p - \Phi_s)} = \tan\Psi e^{i\Delta}, \quad (1)$$

where $\rho_p = |\rho_p| e^{i\Phi_p}$ and $\rho_s = |\rho_s| e^{i\Phi_s}$ are the complex amplitude reflection coefficients.

From these measurements, the thickness and index of refraction of thin-films, and the index of refraction of bulk materials, can be determined. Ellipsometers are employed extensively in science and industry, including the semiconductor and magnetic media industries, where they are used to characterize dielectric and metal films and the indices of refraction of materials.

Classical ellipsometers are non-imaging devices and measure the ellipsometric parameters in a region defined by the focal spot of a beam. In order to map the ellipsometric parameters over a two-dimensional region, the sample must be measured multiple times as it is translated under the ellipsometer. This is a time consuming process that creates a need for imaging ellipsometry.

As two-dimensional focal planes, frame grabbers and computers became more available, powerful and cost effective, researchers in the 1980's began to develop techniques to perform imaging ellipsometry. The classical single point nulling ellipsometer remained

the layout of choice. A number of imaging ellipsometry techniques based on a conventional ellipsometer will be presented.

Interferometry is an accurate tool for the measurement of the phase of optical waves. Modern phase shifting interferometers measure the two-dimensional surface figure of optical parts to the angstrom level in less than a second. Since Δ is a phase measurement, it is a logical extension to use interferometry to measure the ellipsometric parameters.

The measurement of wavefront phase instead of component angular orientation to determine the ellipsometric parameters is a fundamentally different approach to ellipsometry. Research in interferometric ellipsometry began in the early 1970's (Dmitriev 1972, Hazebroek et. al. 1973). The results of these authors, and others, have been impressive but the techniques employed do not provide for imaging ellipsometry.

The phase shifting interferometric imaging ellipsometer unites the techniques of phase shifting interferometry, polarization interferometry and ellipsometry in the development of a novel interferometric imaging ellipsometer. The theory, characterization and calibration of the phase shifting interferometric imaging ellipsometer (PSIIE) will be presented.

The PSIIE is unique in many ways. It utilizes phase shifting interferometry as its acquisition technique and characterizes the ellipsometric parameters of any surface over a two dimensional area. The PSIIE contains no compensator, thereby facilitating multiple wavelength ellipsometry. The modified Michelson arrangement is novel and contains no moving parts, except for a solid state PZT.

Measurements made with the PSIIE indicate a repeatability in the measurement of Δ of between 0.15° and 0.25° . The absolute accuracy of the instrument for samples measured at multiple angles of incidence has a standard deviation of 0.7° - 1° . These results were achieved on a prototype instrument with limited resources. Improvements in the hardware and software of the PSIIE would achieve a repeatability below 0.1° and an absolute accuracy in the same range.

The results of previous work in imaging and interferometric ellipsometry will be presented. The theory of the PSIIE will be presented along with a detailed error analysis. The results of measurements, along with the calibration techniques employed will follow. Recommendations to future investigators will also be discussed.

REVIEW OF CONVENTIONAL ELLIPSOMETRY

There are many applications where knowledge of the thickness of a film is important. In many instances, it is important to know oxide or nitride thickness' to a few angstroms. Contamination of films is also an important issue for some investigators. In the semiconductor industry, metal, metal oxide, or dielectric coatings are often used in the processing of silicon chips. Knowledge of the thickness and composition of the films used is critical to the proper operation of the chips used in modern computers. The technique of ellipsometry provides a solution for many of these problems. Ellipsometry is a nondestructive optical technique that involves the measurement of elliptically polarized light.

When light is reflected at non-normal incidence from a surface, its state of polarization is altered. The change in polarization state is determined by the optical constants (the refractive index n , and the extinction coefficient κ) of the materials involved, as well as a thin-film thickness and index if applicable. Conversely, material indices of refraction and thin-film thicknesses can be determined via this change in polarization state. An ellipsometer measures the state of polarization of light and is a type of polarimeter.

For purely dielectric films (i.e. non-absorbing films), thicknesses from the angstrom level to a few micrometers can be measured with a precision of only a few angstroms (Spannier 1975). Absorbing films can be measured from the angstrom level to a few

thousand angstroms with similar precision. Optical constants are often obtained with accuracies approaching 0.1%.

Ellipsometry must be performed on surfaces with specular reflection and low scatter. Scattering causes depolarization of the beam, which reduces the accuracy and precision of the measurement. Given the above restriction, the substrates for ellipsometric investigation include metal, glass, dielectric, crystalline, and semiconductor materials. The films under investigation can be transparent or absorbing, and the measurement can be made in any transparent environment. Measurements can be made in transmission or reflection, but the term ellipsometry invariably refers to reflection ellipsometry.

THE REFLECTION PROCESS

The ellipticity and azimuth of ellipticity are altered upon non-normal incidence reflection from a substrate or thin-film coated substrate. The mathematics for treating the process of reflection and the state of polarization of a light beam are developed by considering the light beam as two orthogonal electric field components whose coherent superposition represents the electric field of the beam. These components, referred to as the P and S states of polarization, are chosen to be parallel and perpendicular, respectively, to the plane of incidence. The plane of incidence is the plane that contains the incoming ray and the surface normal. Figure 1 details the conventions for the S and P polarization components and the associated electric fields E_P and E_S . In Figure 1 the plane of the

paper is the plane of incidence. The P component is contained in this plane while the S component is perpendicular to the plane of the paper.

Figure 1 Conventions for electric field upon reflection

The two components of the electric field can be represented as follows,

$$E_m(t) = E_m e^{i(\vec{k} \cdot \vec{r} - \omega t + \alpha_m)} \quad m = s, p, \quad (2)$$

where $\vec{k} = \frac{2\pi}{\lambda}(n - i\kappa)\hat{k}$ is the propagation vector, n is the index of refraction, κ is the extinction coefficient, $\hat{k}$ is the propagation direction, ω is the angular frequency, and α_m is the phase of the P or S polarization component.

This phase difference between the S and P components is represented by $\alpha_p - \alpha_s$. Linear polarization is produced if the two polarizations are exactly in phase, or out of phase, with each other (i.e. $\alpha_p - \alpha_s = 0$ or $\pm\pi$). At a phase difference of $\pm(\pi/2)$

circular polarization results. Elliptical polarization is produced by any other phase difference.

The resultant electric field is the vector sum of the polarization components. The ellipse of polarization can be observed in a stationary plane that is perpendicular to the propagation direction, as the locus of the tip of the electric field vector. Figure 2 illustrates a polarization ellipse.

Figure 2 The polarization ellipse

Elliptical polarization can be explained by two quantities, azimuth and ellipticity. The azimuth is the inclination of the major axis from the plane of incidence. This is denoted by Φ in Figure 2. The ellipticity is the ratio of minor to major and is given by $e=b/a$.

A convenient representation of the electric field was developed by Jones (Jones 1941) and is referred to as the Jones vector. It consists of a 2×1 matrix such as

$$\vec{E}(t) = \begin{bmatrix} E_s(t) \\ E_p(t) \end{bmatrix} = \begin{bmatrix} |E_s| e^{i(k \cdot \vec{r} - \omega t + \alpha_s)} \\ |E_p| e^{i(k \cdot \vec{r} - \omega t + \alpha_p)} \end{bmatrix}. \quad (3)$$

The time and space dependence in Equation (3) is common to both polarizations and can be pulled outside to yield

$$\vec{E}(t) = \begin{bmatrix} E_s(t) \\ E_p(t) \end{bmatrix} = \begin{bmatrix} |E_s| e^{i\alpha_s} \\ |E_p| e^{i\alpha_p} \end{bmatrix} e^{i(k \cdot \vec{r} - \omega t)}. \quad (4)$$

For convenience, the time and space dependence will be neglected. The information within the Jones vector contains all the information to determine the state of polarization of the beam.

The complex amplitude reflection coefficients $\rho_p = |\rho_p| e^{i\Phi_p}$ and $\rho_s = |\rho_s| e^{i\Phi_s}$ will modify the amplitude and phase of each polarization component. $|\rho_p|$ and $|\rho_s|$ alter the magnitudes of the electric field, while Φ_p and Φ_s alter the individual phases of the P and S polarizations. Changes in the magnitude of the electric field alter the azimuth of the elliptically polarized wave, whereas, changes in the phase difference alter the ellipticity.

The incident and reflected fields are represented as

$$\vec{E}_{incident} = \begin{bmatrix} E_{i,s} \\ E_{i,p} \end{bmatrix} = \begin{bmatrix} |E_{i,s}| e^{i\alpha_s} \\ |E_{i,p}| e^{i\alpha_p} \end{bmatrix} \text{ and} \quad (5)$$

$$\vec{E}_{reflected} = \begin{bmatrix} E_{r,s} \\ E_{r,p} \end{bmatrix} = \begin{bmatrix} |E_{r,s}| e^{i\beta_s} \\ |E_{r,p}| e^{i\beta_p} \end{bmatrix} = \begin{bmatrix} E_{i,s} \rho_s \\ E_{i,p} \rho_p \end{bmatrix} = \begin{bmatrix} |E_{i,s}| |\rho_s| e^{i(\alpha_s + \Phi_s)} \\ |E_{i,p}| |\rho_p| e^{i(\alpha_p + \Phi_p)} \end{bmatrix}. \quad (6)$$

Taking the ratio of the reflected to incident electric field for each polarization component yields another representation of the reflection process:

$$\rho_m = \frac{E_{r,m}}{E_{i,m}} = \frac{|E_{r,m}|}{|E_{i,m}|} e^{i(\beta_m - \alpha_m)} \quad m = p, s. \quad (7)$$

The phase change on reflection, represented by $(\beta_m - \alpha_m)$ in Equation (7), or by $\Phi_{m = s, p}$ in Equation (10), is not directly measurable. The ratio $\frac{\rho_p}{\rho_s}$ on the other hand yields quantities that are measurable.

A new term ρ contains both amplitude and phase information about the reflection process:

$$\rho = \frac{\rho_p}{\rho_s} = \frac{\frac{E_{r,p}}{E_{i,p}}}{\frac{E_{r,s}}{E_{i,s}}} = \frac{\frac{|E_{r,p}|}{|E_{i,p}|}}{\frac{|E_{r,s}|}{|E_{i,s}|}} e^{i(\delta_r - \delta_i)} = \frac{|\rho_p|}{|\rho_s|} e^{i(\delta_r - \delta_i)}, \quad (8)$$

where $\delta_i = \alpha_p - \alpha_s = \Phi_p$ and $\delta_r = \beta_p - \beta_s = \Phi_s$ are the phase differences between the P and S components before and after reflection respectively. The quantity ρ contains information about the ratio of the P and S components and the phase difference between them. A quantity ρ can be defined for any polarized beam as follows:

$$\rho = \frac{E_p}{E_s} = \frac{|E_p|}{|E_s|} e^{i(\alpha_p - \alpha_s)}. \quad (9)$$

Equation 8 contains all the information needed to describe the state of polarization of a beam of light. Two new quantities, Ψ and Δ , can be defined from Equation (9) as follows:

$$\rho = \frac{\rho_p}{\rho_s} = |\rho| e^{i(\Phi_p - \Phi_s)} = \tan\Psi e^{i\Delta}. \quad (10)$$

Equation (10) represents two quantities that can be measured via ellipsometry. The $\tan\Psi = |\rho| = |\rho_p|/|\rho_s|$ is computed from the measured azimuth (inclination of the major axis from the plane of incidence) and $\Delta = \delta_p - \delta_s = \Phi_p - \Phi_s$ is determined from the ellipticity (the tangent of the ellipticity is the ratio of minor to major axis) of the reflected light. Knowledge, or an independent measurement of the illuminating electric field, will determine these same quantities for the incident electric field.

Ellipsometry is used to measure the change in $\tan\Psi$, the amplitude ratio upon reflection, and Δ the phase difference upon reflection. These quantities are a function of the indices of refraction of the substrate (and film if present) and ambient media, the angle of incidence, the thickness of a thin-film, if present, and the wavelength of the light used. Characterization of Δ and Ψ therefore yields information about these quantities.

THE MEASUREMENT PROCESS

An ellipsometer is an electro-optical instrument containing three main components, a polarization state generator (PSG), a sample holder and a polarization state analyzer (PSA). The PSG produces a polarized, collimated monochromatic beam of light that is reflected from a sample. The polarization state of this beam is then analyzed by the PSA to determine the change in the state of polarization. Precision polarizers and retarding plates are used. The light sources may be fully or partially polarized and common photodetectors or photomultipliers are adequate for the necessary irradiance measurements.

Figure 3 A Photoelectric Research Ellipsometer

In the photoelectric research ellipsometer shown in Figure 3, an incandescent broad band source is passed through a narrow band filter to produce quasi-monochromatic light. This light is collimated and passed through a polarizer and a compensator before being reflected from the sample of interest. After reflection, it passes through an analyzer and travels to a photosensitive detector, or directly to the operators eye.

The polarizers in the system are usually high-quality crystal polarizers and the angular orientation about the optical axis of all of the components is determined to within a fraction of a degree ($\sim 0.01^\circ$). The compensator is an optical retarder that converts linearly polarized light into elliptically polarized light. It imparts a quarter-wave of retardation between the fast and slow axes. The quarter-wave plate is commonly set at $\pm 45^\circ$.

The combination of the polarizer and compensator produces elliptically polarized light with a phase difference α and a ratio of P to S components of $\tan E$. These can be expressed by (Spannier 1975),

$$\tan \alpha = \sin \delta \tan(2P - 90) \text{ and} \quad (11)$$

$$\cos 2E = -\cos \delta \cos 2P, \quad (12)$$

where δ is the retardance of the compensator and P is the orientation of the polarizer in the PSG. Light of any phase difference between the components (α) can be generated via rotation of the polarizer in the PSG. The analyzer in the PSA is used to determine the plane of polarization of the reflected polarized light. Light travels through the PSA to a detector that measured the power level of the transmitted light.

To determine the plane of polarization of the reflected light, the analyzer is rotated to find two minima 180 degrees apart. These minima correspond to the minor axes of the

elliptically polarized light and do not necessarily correspond to true extinction. True extinction occurs with perfect optics and only when the light reflected from the sample is linearly polarized .

For each sample and compensator setting ($\pm 45^\circ$) there is a polarizer orientation that will create an elliptical polarization state that, when reflected from the sample, will result in linear polarization. A “null” is found when the analyzer completely extinguishes the light. The orientation of the polarizer and analyzer that creates this null can be found by alternately rotating each one to deepen the minimum on the intensity meter until a true extinction is obtained. This technique of determining Δ and Ψ via extinguishing the light transmitted by the analyzer is referred to as nulling ellipsometry.

To obtain a true extinction P must be set at an angle P_1 or P_2 so that $\alpha = -\Delta$ or $\alpha = -\Delta + 180$. This can be stated as follows:

$$\begin{aligned} \tan \Delta &= \sin \delta \tan(90 - 2P_1) \text{ and} \\ \tan \Delta &= \sin \delta \tan(270 - 2P_2) \end{aligned} \quad (13)$$

At extinction, the analyzer transmission axis is set to be perpendicular to the orientation of the plane of polarization. This implies that $A=R \pm 90$, where R is the orientation of the linear polarized light given by $\tan R$ as the ratio of R_s/R_p . The ellipsometric parameter Ψ can also be defined as

$$\tan \Psi = \frac{(R_p / R_s)}{(E_p / E_s)}. \quad (14)$$

Therefore, it follows that

$$\tan^2 \Psi = \tan(-A_1) \tan(A_2), \quad (15)$$

where A_1 and A_2 are the analyzer settings corresponding to P_1 and P_2 . Most ellipsometers are either supplied with quarter-wave retarders or contain variable retarders that can be adjusted to a retardation quarter-wave, in which case $\delta = 90^\circ$. In this case the equations relating Δ and Ψ to P and A are simplified to:

$$\begin{aligned} \Delta &= 90 - 2P_1 = 270 - 2P_2 \text{ and} \\ \Psi &= -A_1 = A_2 \end{aligned} \quad (16)$$

DATA INTERPRETATION

Fresnel developed equations for the reflection coefficients of bare surfaces (Born and Wolf 1980). These reflection coefficients derive directly from Maxwell's equations and are different for the S and P polarizations when reflecting at non-normal incidence. The Fresnel reflection coefficients for an interface between two materials with indices of refraction n_0 and n_2 can be stated as follows:

$$\begin{aligned} r_{02p} &= \frac{n_2 \cos \theta_0 - n_0 \cos \theta_2}{n_2 \cos \theta_0 + n_0 \cos \theta_2} \text{ and} \\ r_{02s} &= \frac{n_0 \cos \theta_0 - n_2 \cos \theta_2}{n_0 \cos \theta_0 + n_2 \cos \theta_2} \end{aligned} \quad (17)$$

where θ_0 is the angle of incidence in the incident media and θ_2 is the angle of refraction in the second media. Note that the indices of refraction can be complex, leading to complex values for the angles and the reflection coefficients. The notation $r_{02,p}$ implies the P amplitude reflectance for the interface of materials 0 and 2. For a three media interface (i.e. film coated substrate), 0 refers to the incident media, 1 refers to a thin-film and 2 refers to the substrate.

In 1890 P. Drude treated the problem of film covered surfaces via a summation of the multiple reflections at the ambient film interface and the film substrate interface (Born and Wolf 1980). The resultant reflection of a single thin-film for the S and P polarizations as a function of angle of incidence is given by the following equation:

$$\rho_m = \frac{r_{01m} + r_{12m} e^{-i \frac{4\pi d}{\lambda} n_1 \cos \theta_1}}{1 + r_{01m} r_{12m} e^{-i \frac{4\pi d}{\lambda} n_1 \cos \theta_1}}, m = s, p. \quad (18)$$

In Equation (18), d is the film thickness, n_1 is the complex refractive index of the film, θ_1 is the angle of refraction in the film and λ is the wavelength. By taking the ratio of the P to S reflection coefficients, ρ can be calculated for a given film/substrate combination as a function of angle of incidence and wavelength:

$$\rho = \frac{\rho_p}{\rho_s} = |\rho| e^{i(\Phi_p - \Phi_s)} = \tan \Psi e^{i\Delta} = \frac{\frac{r_{01p} + r_{12p} e^{-i\frac{4\pi d}{\lambda} n_1 \cos \theta_1}}{1 + r_{01p} r_{12p} e^{-i\frac{4\pi d}{\lambda} n_1 \cos \theta_1}}}{\frac{r_{01s} + r_{12s} e^{-i\frac{4\pi d}{\lambda} n_1 \cos \theta_1}}{1 + r_{01s} r_{12s} e^{-i\frac{4\pi d}{\lambda} n_1 \cos \theta_1}}} \quad (19)$$

ρ is a function of the film thickness, indices of refraction of all of the materials involved, angle of incidence, and wavelength. Clearly the functional forms of Ψ and Δ are not straight forward and require the use of a computer for calculation. For a thin-film coated substrate, there are at least six unknowns. Knowledge of the index of refraction of the materials involved (three unknowns), angle of incidence, and wavelength, along with an ellipsometric measurement of Δ and Ψ allows for the calculation of the film thickness. Alternately, the index can be calculated if the thickness is known.

Because there are multiple unknowns, a single ellipsometric measurement of Δ and Ψ at a given angle of incidence cannot determine both the index and thickness of a thin film. Multiple measurements at different angles of incidence (multiple angle of incidence ellipsometry) can yield this information. Solutions to the equations for ellipsometry and calculations involving thin-films are a formidable task that must be performed by a computer.

CONCLUSION

Ellipsometry is a powerful technique for the characterization of thin-films and the index of refraction of materials. Classical ellipsometers operated in null configurations have proven to be highly accurate instruments and are in use in many of today's high technology fields.

A classical ellipsometer can be considered a type of interferometer. Quasi-monochromatic light is used in a common path configuration resulting in interference phenomenon. The S and P polarization components are mutually coherent and the visualization of the polarization ellipse as a coherent vector sum between the two polarizations is inherently an interference phenomenon. The analyzer is acting to take the coherent sum of the S and P polarization components parallel to its transmission axis. This is an interference process.

Classical ellipsometers characterize the ellipsometric parameters over a region defined by the focal spot of a beam (~15-100um) and are therefore non-imaging. In order to characterize a two-dimensional area with a nulling ellipsometer, the instrument would have to step and repeat measurements for each data point, a very time consuming process. The layout does lend itself to some techniques of imaging ellipsometry that will be discussed later.

Classical ellipsometers require components to rotate with high accuracy, and repeatability that complicates the mechanical design of the instruments. Therefore, they do not take advantage of the advances in solid state devices now available.

The layout found in a conventional PCSA ellipsometer could be automated using the technique of phase modulating ellipsometry or via the active rotation of one of the components.

REVIEW OF IMAGING ELLIPSOMETRY

The classical PCSA ellipsometer is a non-imaging device. The focal spot of a beam of light defines the area investigated. This is a limitation for investigators who wish to characterize a two dimensional area. Researchers in thin-film uniformity, magnetic head profilimetry and semiconductor manufacturing are all interested in characterizing the index of refraction of materials and the thickness of thin-films as a function of position.

One area that two dimensional ellipsometry is needed is interferometric profilimetry. When interferometric profilimetry is performed on surfaces with non-uniform film thicknesses or in the case of dissimilar materials within a measurement frame, the phase of the reflected light is affected by the changes in the phase change on reflection as a function of position. If the material indices and film thicknesses are known, the phase change on reflection at normal incidence can be calculated, facilitating correction of the interferometry measurement. An interferometric profilimeter, in conjunction with an imaging ellipsometer could measure many samples that are currently unmeasurable. This is a major impetus for the development of the phase shifting imaging ellipsometer.

As two-dimensional focal planes, frame grabbers and computers became more available, powerful and cost effective, researches began to develop techniques to perform imaging ellipsometry. The PCSA (polarizer, compensator, sample and analyzer) remained the

layout of choice. The only difference being the addition of imaging optics for imaging the surface under test to a focal plane array.

Figure 4 illustrates the most common layout of an imaging ellipsometer. The light from the source is collimated to uniformly illuminate the sample, following transmission through a polarizer and compensator. The light reflected from the sample is imaged onto the CCD by the imaging optics. The light passes through a second polarizer, the analyzer, before encountering the CCD array.

Figure 4 Layout of a generic imaging ellipsometer based on a PCSA layout

The challenge in imaging ellipsometry is the development of an algorithm that will characterize the ellipsometric parameters without the use of nulling.

When looking at two-dimensional area of a non-uniform thin-film, it is impossible to null the entire frame with a single set of component orientations. Any nulling technique has

only limited success for imaging ellipsometry. The ellipsometric parameters are characterized only in the regions where a null is achieved.

Previous work in imaging ellipsometry falls into two basic classes. The first relies on nulling techniques for data acquisition. Frames of data are acquired with a variety of polarizer or compensator settings and the corresponding nulled regions are mapped out. Only regions that achieved nulls in one of the frames have their ellipsometric data characterized. The regions between the nulls can be interpolated.

The second class of imaging ellipsometers use radiometric techniques. Multiple-frame algorithms determine Ψ and Δ data over the entire two-dimensional area being investigated.

NULLING TECHNIQUES

Consider a system as shown in Figure 4 when there are significant variations in film thickness on the sample under test. This change in film thickness as a function of position causes variations in the reflected state of polarization. The polarizer and compensator can be rotated to achieve a null somewhere on the surface. Because of variations in the film's thickness, the null will not be over the entire surface, but will trace out the regions in the sample with constant Ψ and Δ values. These nulls contour the surface much like a topographic map. In fact, if the variations are large enough, there can be multiple nulls, corresponding to different film thickness that have the same

ellipsometric parameters. These nulls are analogous to fringes in an interference pattern; in fact, they are interference fringes, because ellipsometry is an interference phenomenon.

Each contiguous null corresponds to regions on the surface that have the same ellipsometric parameters. In these regions, the ellipsometric parameters have been uniquely determined. A series of measurements with different polarizer and compensator settings can map out the surface more completely, identifying multiple film thickness contours. A series of measurements, coupled with the assumption of film thickness continuity, can map out the entire surface. The regions between the contours can be linearly interpolated to achieve two-dimensional data between the contours.

This is the basic technique outlined by a number of authors (Mishima and Kao 1981, 1982; Beaglehole 1988; Liu, Wayner and Plawsky 1994; Adachi, Yoshimura and Nagayama 1995).

IMAGE SCANNING ELLIPSOMETER

In a paper by Liu et. al. (1994) theoretical and experimental data are discussed. The “Image Scanning Ellipsometer” was used to measure a smoothly varying non-uniform film of ThF₄ using the illustrated in Figure 4. The technique operates by fixing the analyzer and compensator settings. The polarizer is then rotated, upon which one can observe that the null points, or contours of nulls, which have a minimum reflectivity, sweep across the whole measuring area.

Successive images are taken with different analyzer settings to construct a profile of the coating thickness that can vary from several nanometers to several microns. The more settings used on the polarizer, the more points that are contoured in the film thickness profile. The choice of angles depends on the optical properties of the substrate and film. For the ThF₄ film, eleven polarizer settings were used to characterize the surface and eleven separate frames of data were required to characterize the film. The lateral resolution of the system was found to be 2 μ m x 7.5 μ m and a film thickness accuracy 5nm was quoted. It is evident that this accuracy contained a large amount of averaging over the surface. The repeatability or noise level on a point by point basis was not quoted.

THE SPATIALLY RESOLVED ELLIPSO-INTERFEROMETER

Utilizing the same technique in an instrument titled “the spatially resolved ellipso-interferometer”, Mishima and Kao (1982) claim a lateral resolution of 1.5 μ m and a film thickness accuracy of less than 10nm for their measurements.

These techniques are limited to the investigation of smoothly varying thin-films. Because they operate via the tracking of null contours, abrupt changes in ellipsometric parameters may not be detected if a contour does not intersect the discontinuity. Surfaces containing regions with radically different ellipsometric parameters are unmeasurable. The accuracies of the technique are not as good as standard single point nulling

ellipsometry but, for some investigators, the advantage of two-dimensional measurements is worth the sacrifice in accuracy.

MULTIPLE FRAME ALGORITHM TECHNIQUES

Realizing the limitation in the nulling techniques, investigators developed radiometric algorithms that characterize the ellipsometric parameters. Radiometric ellipsometry uses the magnitudes of the detected light from multiple frames to determine the ellipsometric parameters. Each frame of data uses different component (polarizer, compensator or analyzer) settings. The acquired data is entered in an algorithm to determine the ellipsometric parameters of the surface under test. This is analogous to phase shifting interferometry where multiple frames of data are used to calculate the phase of an interferogram.

Two algorithms for performing radiometric ellipsometry have been identified. They both use the layout shown in Figure 4.

DYNAMIC IMAGING MICROELLIPSOMETER

Ralph F Cohn, James W Wagner and Jerome Kruger (1988) developed a "Dynamic Imaging Microellipsometer," that uses four compensator rotations to measure the ellipsometric parameters. A radiometric approach is employed, using the linearity and stability of CCD detector arrays to record the light intensity at three or more instrument

settings. The Δ and Ψ full field maps, referred to as ellipsograms, are calculated from the intensity distributions and known instrument settings.

The measurement technique involves taking frames of data at multiple compensator settings while leaving the polarizer and compensator settings unchanged. The development of the system is derived using the Jones matrix approach. P , C and A represent the polarizer compensator and analyzer rotational orientations. The intensity at the focal plane can be represented by the following equation:

$$I(A) = \frac{G^2}{2} \{ [1 + \cos(2C) \cos 2(P - C)] \cos^2(A) \tan^2 \Psi + [1 - \cos 2C \cos 2(P - C)] \sin^2 A + [\sin 2C \cos 2(P - C) \cos \Delta - \sin 2(P - C) \sin \Delta] \sin 2A \tan \Psi \} \quad (20)$$

Note that Equation (20) contains six variables, P , C , A , G , Δ and Ψ , where G is the system gain. Angles P and C are the polarizer and compensator rotational settings and are set to known and fixed values. The analyzer angle A is the control variable, which is rotated to selected positions at which the intensity is recorded. Three unknown variables remain at each point in the field, the system gain G and the two ellipsometric parameters Δ and Ψ . Therefore, a minimum of three analyzer settings is required to obtain three equations of $I(A)$, which are then solved to determine the ellipsometric parameters Δ and Ψ at every point in the field. Using four analyzer settings simplifies the resultant equations for Δ and Ψ . Using compensator settings of -45° , 0° , 45° and 90° the equations for Δ and Ψ are:

$$\begin{aligned}
\Psi &= \tan^{-1} \left[\frac{\sqrt{1 - \cos 2C \cos 2(P - C)}}{\sqrt{1 + \cos 2C \cos 2(P - C)}} \sqrt{\frac{I(0^\circ)}{I(90^\circ)}} \right] \\
\Delta &= \cos^{-1} \left[\frac{I(45^\circ) - I(-45^\circ)}{2\sqrt{I(0^\circ)I(90^\circ)}} \right] - \tan^{-1} \left[\frac{\tan 2(P - C)}{\sin 2C} \right] .
\end{aligned} \tag{21}$$

The authors note two important concepts in the above equations. Firstly, neither the input light intensity nor the attenuation of the optical system enter into the equations for Δ and Ψ . Therefore, if the system gain is held constant during the data acquisition, no calibration of system gain is required. Secondly, the terms involving the compensator and polarizer rotational settings are separable from the image intensity terms. This allows for errors in the component settings to be calibrated out via the measurement of a reference sample.

In their error analysis, the authors note that in order to achieve high accuracy, the rotational orientation of the two fixed components (P and C) must be customized to reduce the effects of noise, angle characterization and other effects. Models indicated errors in Δ that ranged from 0.1° for an optimized system to $1-5^\circ$ for the worst case scenario. Errors in Ψ ranged from 0.05° to 0.25° . Actual measurements of a well-polished silicon wafer yielded RMS noise errors of 0.36° for Δ and 0.082° for Ψ . Peaks to valley variations were 2.5° for Δ and 0.3° for Ψ .

2D IMAGING ELLIPSOMETRIC MICROSCOPE

Huyk K Pak and Bruce M Law (1995) developed a “2D imaging ellipsometric microscope.” The layout shown in Figure 5 uses a liquid crystal phase modulator instead of a quarter-wave plate for the compensator.

Figure 5 2D imaging ellipsometric microscope

The operation of the instrument is different from any of the ellipsometers discussed. Instead of changing the orientation of the polarizer and analyzer to obtain a null or a multi-step algorithm, a liquid crystal phase modulator is varied from frame to frame. In this way, it is similar to the Phase Modulating Ellipsometer discussed in the section on interferometric ellipsometry. In the PMA, the phase of the modulator is varied in a continuous fashion to perform heterodyne interferometry. In this case, the phase is altered in discrete steps to perform what might be called phase stepping ellipsometry.

This ellipsometer therefore can be considered an interferometric imaging ellipsometer. It will be seen though, that the data acquisition techniques used by Pak and Law are different than that found in interferometry and in the phase shifting interferometric imaging ellipsometer.

The initial polarizer is oriented at 45° to generate an unbiased reference wave that has identical amplitudes and phase in and perpendicular to the plane of incidence. The Jones matrix for the beam exiting the polarizer is given by Equation (22):

$$E = \begin{bmatrix} A_o e^{i\Phi_o} \\ A_o e^{i\Phi_o} \end{bmatrix} = A_o e^{i\Phi_o} \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \quad (22)$$

The light then transmits through the liquid crystal phase modulator. The Jones matrix for the liquid crystal is given by Equation (23)

$$J_{P.P.S.} = \begin{bmatrix} 1 & 0 \\ 0 & e^{i(\Phi_{LC})} \end{bmatrix}, \quad (23)$$

where Φ_{LC} is the phase induced by the phase modulator. In this case, the phase of the p component is being shifted with respect to the s component. Following reflection from the sample the electric field is altered by the complex reflection or transmission coefficients of the sample and can be represented by Equation (24).

$$E_{reflected} = J_{Sample} E_{Incident} = \begin{bmatrix} \rho_s & 0 \\ 0 & \rho_p \end{bmatrix} \begin{bmatrix} 1 \\ e^{i(\Phi_{LC})} \end{bmatrix} = \begin{bmatrix} \rho_s \\ \rho_p e^{i(\Phi_{LC})} \end{bmatrix}. \quad (24)$$

Following transmission through the analyzer the beam is represented by:

$$\begin{aligned}
 E &= \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \rho_s \\ \rho_p e^{i(\Phi_{LC})} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \rho_s + \rho_p e^{i(\Phi_{LC})} \\ \rho_s + \rho_p e^{i(\Phi_{LC})} \end{bmatrix} = \\
 &= \frac{1}{2} \begin{bmatrix} |\rho_s| e^{i(\Phi_s)} + |\rho_p| e^{i(\Phi_p + \Phi_{LC})} \\ |\rho_s| e^{i(\Phi_s)} + |\rho_p| e^{i(\Phi_p + \Phi_{LC})} \end{bmatrix} .
 \end{aligned} \tag{25}$$

Both components are the coherent sum of two independent terms caused by transmission through the polarizer. This is the defining characteristic of an interference pattern. The phase and intensity in the s and p components are identical to one another and therefore contain the same information. The interference pattern that results is:

$$I = \frac{1}{4} \left\{ |\rho_s|^2 + |\rho_p|^2 + 2|\rho_s||\rho_p| \cos(\Phi_p - \Phi_s + \Phi_{LC}) \right\} . \tag{26}$$

Equation (26) can be rearranged to yield

$$I = \frac{1}{4} |\rho_s|^2 \left\{ 1 + |\rho|^2 + 2|\rho| \cos(\Delta + \Phi_{LC}) \right\} , \tag{27}$$

where,

$$\begin{aligned}
 \rho &= \frac{\rho_p}{\rho_s} = \frac{|\rho_p|}{|\rho_s|} e^{i(\Phi_p - \Phi_s)} = \tan \Psi e^{i\Delta} \text{ and} \\
 \tan\{\Psi\} &= \frac{|\rho_p|}{|\rho_s|} , \text{ and} \\
 \Delta &= \Phi_p - \Phi_s
 \end{aligned} \tag{28}$$

In order to extract Δ and Ψ from the interference pattern, the authors take four frames of data with Φ_{LC} equal to $0, \pi/2, \pi$ and $3\pi/2$. Equations (29) and (30) detail the algorithm used to calculate ρ :

$$\frac{I_0 - I_\pi}{I_0 + I_\pi} = \frac{2|\rho|\cos\Delta}{1+|\rho|^2} \cong 2|\rho|\cos\Delta = 2\operatorname{Re}\rho \quad \text{and} \quad (29)$$

$$\frac{I_{\pi/2} - I_{3\pi/2}}{I_{\pi/2} + I_{3\pi/2}} = \frac{2|\rho|\sin\Delta}{1+|\rho|^2} \cong 2|\rho|\sin\Delta = 2\operatorname{Im}\rho. \quad (30)$$

In deriving Equations (29) and (30), the authors assumed that $|\rho|^2 \ll 1$ which is true when the film is being evaluated at the Brewster angle of the substrate and for films whose thickness is less than the wavelength of light. At the Brewster angle, where $\Delta = \pi/2$, and the real component of ρ vanishes.

For films whose thickness is much less than the wavelength of light on a substrate of known index of refraction, this instrument can measure the ellipsometric parameters. The algorithm developed for this instrument cannot measure samples with a variety of substrates in a single measurement because of the Brewster angle requirement, nor can it measure unknown samples.

Although it is not clear the authors of this work were aware of it, the use of phase shifting interferometry (PSI) would allow this instrument to measure the ellipsometric parameters of any sample/film combination.

Using the same four frames of data, the algorithm used by the authors can be modified to perform phase shifting interferometry. The phase and modulation of the interferogram can be found from Equation (26):

$$\text{Phase} = \Phi_p - \Phi_s = \Delta, \text{ and} \quad (31)$$

$$\text{Visibility} = V = \frac{2|\rho_s||\rho_p|}{|\rho_s|^2 + |\rho_p|^2} = \frac{AC\{V\}}{DC\{V\}}. \quad (32)$$

The phase and modulation of the interference pattern can be found using phase shifting interferometry:

$$\Phi = \text{ArcTan} \left[\frac{(I_{3\pi/2} - I_{\pi/2})}{(I_0 - I_{\pi/2})} \right] \quad (33)$$

$$\gamma = \frac{2 * \sqrt{[I_{3\pi/2} - I_{\pi/2}]^2 + [I_0 - I_{\pi}]^2}}{I_0 + I_{\pi/2} + I_{\pi} + I_{3\pi/2}}$$

The measured phase of the interferogram is exactly Δ while it does not appear as though the visibility yields the information necessary for calculating the ratio of reflectances, $\tan \Psi$. Because phase shifting interferometry allows for the calculation of both the numerator and denominator independently, ρ_s and ρ_p can be determined unambiguously from the two equations with two unknowns. Therefore, this layout in conjunction with a polarization phase shifter and phase shifting interferometry can characterize the ellipsometric parameters of any surface.

Lateral resolution is quoted at 1 μm and thickness accuracies are quoted in the angstrom level for films ($t \ll \lambda$) measured at their respective Brewster angle. Pak and Law note the following advantages to their ellipsometer. It has no moving components eliminating vibration and misalignment problems. The algorithm works in the presence of pixel to

pixel gain variations and in the presence of source light spatial variations. Because the layout is common path, vibration isolation is not required.

REVIEW AND CONCLUSIONS

Radiometric algorithm techniques are superior to the nulling techniques in many ways. They are able to characterize any type of surface, not just smoothly varying films. Only three or four frames of data are required. Surfaces with any structure can be measured, provided the optical resolution is sufficient. The accuracy of the measurement is not always optimized for a given film-substrate combination, but if desired, multiple measurements can be made with different component settings to optimize the measurements. The use of phase shifting interferometry techniques in the 2D imaging ellipsometric microscope allows for the characterization of the ellipsometric parameters of any substrate or substrate/film combination.

Only the Dynamic Imaging Micro-ellipsometer is versatile enough as presented by the original authors to measure the ellipsometric parameters of any substrate or substrate film combination. Improving the 2D Imaging Ellipsometric Microscope by using phase shifting interferometry would allow it to measure any surface as well.

REVIEW OF INTERFEROMETRIC ELLIPSOMETRY

The techniques of classical ellipsometry developed in the 1960's proved useful for the characterization of the index of refraction of materials and thin films and for the characterization of film thicknesses. By the early 1970's, it had been successfully employed in the study of adsorbed films of thicknesses as small as fractional mono-layers and with an experimental accuracy within $\pm 1 \text{ \AA}$ (Hazebroek H H, Holscher A A 1973). In this chapter, a review of previous work in the field of interferometric ellipsometry will be presented and compared to the techniques of classical ellipsometry. A brief review of interferometry will be presented followed by a variety of interferometric ellipsometers.

In classical ellipsometry, the polarization ellipse is characterized via the specific rotational orientation of a polarizer, compensator and an analyzer. The compensator, usually a quarter-wave plate, can be thought of as an optical phase shifter. It changes the relative phase between the S and P components, to create elliptically polarized light.

The measurement method involves the rotation of the polarizer and analyzer to achieve a null output. Independent mechanical rotation of two components is required to operate the instrument. To minimize systematic errors, multiple null conditions can be used, thereby increasing measurement time. Radiometric techniques have also been proposed (Hauge P. S. and Dill F. H. 1973). One such technique uses a synchronously rotating analyzer to detect the state of polarization of light after its reflection from a surface.

Other techniques involve the use of Faraday rotators or Pockels cells. These techniques are based on the PCSA ellipsometer, are well proven, and work well. One of these techniques, the phase modulated ellipsometer is a good illustration of interferometric ellipsometry.

Interferometric ellipsometry is a fundamentally different approach to the measurement of the ellipsometric parameters. The optical phase of between two arms of an interferometer is used to calculate the ellipsometric parameters, instead of the rotational orientation of polarizers and compensators.

Interferometry is a common optical technique involving the coherent superposition of two or more optical wave fronts. The Michelson interferometer (Michelson A A, 1881) is a classic example of an interferometer. A schematic of a Michelson interferometer is found in Figure 6.

Figure 6 Michelson interferometer

An extended broad band source is collimated and directed toward a plane parallel plate beam splitter G1. This plate has a partially reflecting coating on the rear surface and an anti-reflection coating on the front.

The light is transmitted through the front surface of the plate. One beam is reflected by the rear surface and traverses through the plate again on its way to the return mirror M1. The beam is reflected by M1 and transmits through the beam splitter (G1). Mirror M1 can be translated by turning a micrometer screw to equalize the optical path lengths in the two arms in order to obtain fringes from a broad band source. Note that this beam travels through the plane parallel plate beam splitter three times.

The other beam travels towards M2 but first encounters another plane parallel plate called a compensator. This compensator is used to equalize the path lengths in the glass material. This compensator has the same thickness and tilt as the beam splitter. Following reflection from M2 the beam returns to the beam splitter where it is reflected. Interference occurs when the beam splitter recombines the two beams. The corresponding interference pattern is given by:

$$\begin{aligned}
 I_{coherent} &= \langle (E_{coherent})^2 \rangle = \langle (E_1 + E_2)^2 \rangle = \langle E_1^2 + E_2^2 + 2E_1E_2 \rangle \\
 &= |E_1|^2 + |E_2|^2 + |2E_1E_2|, \quad (34) \\
 &= I_1 + I_2 + 2\sqrt{I_1I_2}\cos(\alpha)
 \end{aligned}$$

where α is the phase difference between the two electric fields. The maximum and minimum intensities of a coherent superposition occur when α equals 0 or π and are therefore:

$$\begin{aligned} I_{\max} &= I_1 + I_2 + 2\sqrt{I_1 I_2} \\ I_{\min} &= I_1 + I_2 - 2\sqrt{I_1 I_2} \end{aligned} \quad (35)$$

Fringe visibility is defined as:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{I_{AC}}{I_{DC}}, \quad (36)$$

and varies from 0 to 1. I_{AC} and I_{DC} represent the AC and DC components of the interference pattern as illustrated in Figure 7. Fringe visibility is a measure of how “strong” the fringe pattern is. The fringes are the strongest when $V=1$ and are non-existent when $V=0$.

Figure 7 A sample fringe pattern

The fringe pattern contains information about the two interfered wave fronts. When the path lengths of the two arms are identical and no tilt is present between the two mirrors, a central dark fringe will appear. When tilt is introduced, straight-line fringes will be observed. When the paths are unequal but no tilt is present, circular fringes will be seen.

If a point source is used in a Michelson interferometer, a more useful interferometer is obtained. The Twyman-Green (Born and Wolf 1980) interferometer as it is called, uses plane parallel wave fronts and is a powerful instrument for testing the surface profile of prisms, lenses and mirrors. Surface height variations of a fraction of the wavelength of light can be detected through simple visual examination of the fringe pattern. In a modern phase shifting interferometer (PSI) surface height variations of 1/100-1/1000 of the wavelength of light can be detected.

The phase and the fringe visibility of an interference pattern can be characterized by shifting the relative phase of one arm with respect to the other in a prescribed fashion, and acquiring a minimum of three frames of data. For a four-step algorithm, four frames of data are taken which differ in phase by a quarter-wave. If the intensity of the fringe pattern for each of four interferograms is represented by:

$$\begin{aligned}
 & I_n(x, y) \text{ for } n = 1 - 4 \\
 I_{coherent} &= \langle (E_{coherent})^2 \rangle = \langle (E_1 + E_2)^2 \rangle = \langle E_1^2 + E_2^2 + 2E_1E_2 \rangle \\
 &= |E_1|^2 + |E_2|^2 + 2|E_1E_2| \cos(\alpha + \Phi_{psi}^n)
 \end{aligned} \tag{37}$$

The phase and modulation of the interferogram can be calculated:

$$\Phi(x, y) = \text{ArcTan} \frac{I_4(x, y) - I_2(x, y)}{I_1(x, y) - I_3(x, y)}, \text{ and} \quad (38)$$

$$V(x, y) = \frac{2\sqrt{(I_4(x, y) - I_2(x, y))^2 + (I_1(x, y) - I_3(x, y))^2}}{I_1(x, y) + I_2(x, y) + I_3(x, y) + I_4(x, y)} = \frac{AC\{V\}}{DC\{V\}}. \quad (39)$$

POLARIZATION INTERFEROMETRY AND INTERFEROMETRIC ELLIPSOMETRY

In order to perform interferometric ellipsometry, an arrangement must be developed in which information gathered from an interference pattern determines the state of polarization of light. Direct interference between the two polarization components via a polarizer oriented at 45° is one technique to accomplish this. Another technique is to separately interfere each component with a common reference beam.

In order to understand these two approaches, consider the Jones matrix for polarized light at $\theta = 45^\circ$ for use as a source beam in an interferometric ellipsometer. It is given by:

$$E_{\text{Source}} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad (40)$$

where a common term $\sqrt{2}/2$ has been dropped for clarity. Following reflection from a sample, the electric field is:

$$E = J_{\text{sample}} E_{\text{Source}} = \begin{bmatrix} \rho_s & 0 \\ 0 & \rho_p \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \rho_s \\ \rho_p \end{bmatrix} = \begin{bmatrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{bmatrix}, \quad (41)$$

where $\rho_p = |\rho_p|e^{i\Phi_p}$ and $\rho_s = |\rho_s|e^{i\Phi_s}$ are the amplitude reflection coefficients for the sample of interest. All the information necessary to calculate the two ellipsometric parameters is contained within this matrix. To review again, the ellipsometric parameters Δ and Ψ are defined in terms of the complex amplitude reflection coefficients for the S and P polarizations:

$$\rho = \frac{\rho_p}{\rho_s} = \frac{|\rho_p|}{|\rho_s|} e^{i(\Phi_p - \Phi_s)} = \tan\Psi e^{i\Delta}. \quad (42)$$

Therefore,

$$\begin{aligned} \tan\{\Psi\} &= \frac{|\rho_p|}{|\rho_s|}, \text{ and} \\ \Delta &= \Phi_p - \Phi_s, \end{aligned} \quad (43)$$

In order to measure Ψ , the ratio of the magnitudes of the P and S electric field must be measured. It will be shown that fringe visibility can be used to calculate the ellipsometric parameter Ψ .

Examination of Equation 1 indicates that the phase of the electric field for each polarization contains the phase change on reflection for the sample of interest for that polarization. Therefore, if we take the argument of each of the two orthogonal polarization directions in Equation 1 the following simple result is obtained,

$$\text{Arg}\{E_{\text{sample}}\} = \text{Arg}\left\{\begin{bmatrix} E_s \\ E_p \end{bmatrix}\right\} = \text{Arg}\left\{\begin{bmatrix} |\rho_s|e^{i\Phi_s} \\ |\rho_p|e^{i\Phi_p} \end{bmatrix}\right\} = \begin{bmatrix} \Phi_s \\ \Phi_p \end{bmatrix}. \quad (44)$$

and it directly follows that the ellipsometric parameter Δ is found to be:

$$\Delta = \text{Arg}\{E_p\} - \text{Arg}\{E_s\} = \Phi_p - \Phi_s. \quad (45)$$

If the phase of each component can be measured using interferometry, Δ can be determined.

As mentioned earlier, there are two general techniques for obtaining the proper phase profile in an interferometric ellipsometer. Examination of Equation (41) can be used to illustrate the first of these. If the S and P beams are interfered via a polarizer at 45° , the phase of the resulting pattern will be the difference in phases between the two beams. This phase difference defines the ellipsometric parameter Ψ .

PHASE MODULATING ELLIPSOMETER (PME)

A layout that utilizes the direct interference of the two polarization components is found in Figure 8.

Figure 8 A Phase Modulating Ellipsometer (Hauge P. S. 1980).

The source is polarized at 45° by a polarizer before passing through a polarization phase shifter. Following reflection from sample, the light passes through a polarizer oriented at 45° . This polarizer interferes the S and P components.

The polarization phase shifter introduces a phase difference between the S and P polarizations. The phase difference between the two components can be varied in time to perform phase shifting interferometry. This is similar in concept to a piezo-electric transducer in a Twyman-Green or Fizeau interferometer. The Jones matrix for an ideal polarization phase shifter (P.P.S.) is given by:

$$J_{P.P.S.} = \begin{bmatrix} 1 & 0 \\ 0 & e^{i(\Phi_{PSI})} \end{bmatrix}, \quad (46)$$

where Φ_{PSI} is the phase introduced by the phase shifter for phase shifting interferometry. In this case, the phase of the P component is being changed with respect to the S component.

To perform phase shifting interferometry, the polarization phase shifter introduces a series of quarter-wave phase differences between the S and P components. Liquid crystal phase modulators, Pockels cells, and Soleil-Babinet compensators are examples of polarization phase shifters.

The Jones matrix for the beam incident on the sample is:

$$E_{Incident} = J_{P.P.S.} E_{Illumination} = \begin{bmatrix} 1 & 0 \\ 0 & e^{i(\Phi_{PSI})} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ e^{i(\Phi_{PSI})} \end{bmatrix}. \quad (47)$$

Following reflection from the sample, the electric field can be represented by:

$$E_{reflected} = J_{Sample} E_{Incident} = \begin{bmatrix} \rho_s & 0 \\ 0 & \rho_p \end{bmatrix} \begin{bmatrix} 1 \\ e^{i(\Phi_{PSI})} \end{bmatrix} = \begin{bmatrix} \rho_s \\ \rho_p e^{i(\Phi_{PSI})} \end{bmatrix}. \quad (48)$$

Following transmission through the polarizer, the beam is represented by:

$$E_{reflected} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \rho_s \\ \rho_p e^{i(\Phi_{PSI})} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \rho_s + \rho_p e^{i(\Phi_{PSI})} \\ \rho_s + \rho_p e^{i(\Phi_{PSI})} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} |\rho_s| e^{i(\Phi_s)} + |\rho_p| e^{i(\Phi_p + \Phi_{PSI})} \\ |\rho_s| e^{i(\Phi_s)} + |\rho_p| e^{i(\Phi_p + \Phi_{PSI})} \end{bmatrix}. \quad (49)$$

At this point, we see that both polarization components are the coherent sum of two independent terms. This is the defining characteristic of an interference pattern. The interference pattern that results is:

$$I = \frac{1}{4} \left\{ |\rho_s|^2 + |\rho_p|^2 + 2|\rho_s||\rho_p| \cos(\Phi_p - \Phi_s + \Phi_{PSI}) \right\}. \quad (50)$$

By varying Φ_{PSI} , phase shifting interferometry is performed. The following phase and visibility are obtained:

$$\text{Phase} = \Phi_p - \Phi_s = \Delta \text{ and} \quad (51)$$

$$\text{Visibility} = V = \frac{2|\rho_s||\rho_p|}{|\rho_s|^2 + |\rho_p|^2} = \frac{AC\{V\}}{DC\{V\}}. \quad (52)$$

The measured phase of the interferogram is Δ , while it does not appear as though the visibility yields the information necessary for calculating Ψ . Because phase shifting

interferometry allows for the calculation of both the numerator and denominator of Equation (52) independently, ρ_s and ρ_p can be determined unambiguously from the two equations with two unknowns. Therefore, this layout can characterize the ellipsometric parameters.

The layout presented by Hague (Hauge P. S. 1980) is identical to that presented here except that heterodyne interferometry was used to measure the ellipsometric parameters. The interference pattern is Doppler shifted by modulating the polarization phase shifter in an AC fashion. The techniques presented by Hague are single point measurements using a single detector and are not applicable to imaging ellipsometry.

PSI techniques, although slower, are directly applicable to two-dimensional measurements. Imaging ellipsometers utilizing a similar PCSA layout will be described in the chapter on imaging ellipsometers. It will be shown that these instruments can perform imaging ellipsometry using phase shifting ellipsometry or other radiometric techniques.

One advantage of this layout is its common path nature. With the sample removed, the system can be calibrated, enabling absolute measurements. There are no moving parts and the system is computer controlled. Because the crystals used in the variable retarder can modulate in fractions of a second, the speed of operation is only limited by the speed

of the detector. For single point measurements using a lock in amplifier, the system could yield hundreds of measurements a second.

Disadvantages of the system involve the cost and operation of the phase modulating crystals. In addition to being expensive, the crystals often exhibit variation in the phase retardance across the aperture. The variation of the phase retardance with applied voltage can as large as 5% in the case of liquid crystals. Variations across the aperture or between steps would cause significant errors in the resulting measured phase and visibility. Operation of the instrument in an AC mode, as presented by Hague, greatly reduces these effects because the measured AC signal can be averaged over many cycles while still yielding many measurements a second.

The use of a variable compensator, as in the PME, is a logical extension of the techniques of classical ellipsometry. Taking advantage of modern technology (electrically varying compensators, computer control and analysis, fast photodetectors and lock in amplifiers) the PME extends the speed, ease of use and accuracy of the manually operated PCSA ellipsometer.

The phase shifting PME is an example of an interferometric ellipsometer that interferes the S and P components with each other to obtain information about the phase difference between the components and the ratio of their magnitudes. This example has a layout that is identical to the PCSA ellipsometer.

INTERFEROMETRIC ELLIPSOMETERS UTILIZING INTERFERENCE WITH A REFERENCE BEAM

The ellipsometers that follow resemble interferometers more than they do a PCSA ellipsometer. Two distinct and spatially separated light paths are created with the use of beam splitters. The multiple beam nature of an interferometer is a noticeable distinction between the classical ellipsometer and the work to follow in interferometric ellipsometry. These interferometers also fall into a class of instruments called polarization interferometers.

These interferometers operate by having two interference patterns, one each for the S and P components. This is a fundamental change from a classical PCSA ellipsometer or the PME. These instruments interfere each polarization with a common reference beam and in the process characterize the polarization ellipse. The difference in the phase between the S and P interferograms plays an essential role in these instruments and is the method for measuring the ellipsometric parameter Δ . Intensity information in the interferograms is used to measure Ψ .

Beginning with an elliptically polarized beam called the test beam:

$$E_{test} = \begin{bmatrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{bmatrix}, \quad (53)$$

where $|\rho_s|$ and $|\rho_p|$ are the amplitudes of the electric fields and Φ_s and Φ_p are the phases of the electric field for the S and P polarizations respectively. The state of polarization, amplitude and absolute phase of the beam can be determined via the four parameters $|\rho_s|$, $|\rho_p|$, Φ_s and Φ_p . Characterization of the polarization ellipse requires only two parameters, Δ and Ψ that are defined via the ratio of the electric fields in the P and S direction.

Another beam of light, polarized at 45° , is called the reference beam:

$$E_{reference} = \begin{bmatrix} |A_o|e^{i\Phi_o} \\ |A_o|e^{i\Phi_o} \end{bmatrix} = |A_o|e^{i\Phi_o} \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad (54)$$

where the term $|A_o|$ refers to the arbitrary electric field magnitude for the reference beam. This term will be used throughout these sections describing interferometric ellipsometers.

This reference beam is essential in the process because it provides an unbiased reference source for the S and P components. The resulting electric field and intensity pattern from the coherent interference between these two beams are

$$E = E_{test} + E_{reference} = |A_o|e^{i\Phi_o} \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} |\rho_s|e^{i\Phi_s} \\ |\rho_p|e^{i\Phi_p} \end{bmatrix} = \begin{bmatrix} |A_o|e^{i\Phi_o} + |\rho_s|e^{i\Phi_s} \\ |A_o|e^{i\Phi_o} + |\rho_p|e^{i\Phi_p} \end{bmatrix} \text{ and} \quad (55)$$

$$I = \begin{bmatrix} I_o + I_s + 2|A_o||\rho_s|\cos(\Phi_o - \Phi_s) \\ I_o + I_p + 2|A_o||\rho_p|\cos(\Phi_o - \Phi_p) \end{bmatrix}.$$

Valuable polarization phase and intensity based information can be obtained if each polarization has its own interference pattern.

$$\begin{aligned} I_s &= I_o + I_s + 2|A_o||\rho_s|\cos(\Phi_o - \Phi_s) \\ I_p &= I_o + I_p + 2|A_o||\rho_p|\cos(\Phi_o - \Phi_p) \end{aligned} \quad (56)$$

These intensity equations contain information about the polarization ellipse. The phase of each pattern can be determined and expressed as follows:

$$\begin{aligned} \text{Phase}_s &= (\Phi_o - \Phi_s) \\ \text{Phase}_p &= (\Phi_o - \Phi_p) \end{aligned} \quad (57)$$

The individual phases of the patterns do not yield useful information because of the arbitrary phase of the reference beam Φ_o . The difference between the S and P phases is:

$$\text{Phase}_s - \text{Phase}_p = (\Phi_o - \Phi_s) - (\Phi_o - \Phi_p) = \Phi_p - \Phi_s = \Delta, \quad (58)$$

which is the ellipsometric parameter Δ . In other words, the difference between the phases of the S and P interference patterns is Δ .

The interference patterns contain intensity information that can be used to measure Ψ .

The fringe visibility of the S and P interference patterns are given by:

$$\begin{aligned} V_s &= \frac{2|A_o||\rho_s|}{I_o + I_s} \\ V_p &= \frac{2|A_o||\rho_p|}{I_o + I_p} \end{aligned} \quad (59)$$

In order to calculate the state of polarization of the test beam the ratio $|\rho_p| / |\rho_s|$ is required. The ratio of the AC components of the interferogram modulation yields a method for measuring Ψ :

$$\frac{AC\left\{V_p\right\}}{AC\left\{V_s\right\}} = \frac{2|A_o||\rho_p|}{2|A_o||\rho_s|} = \frac{|\rho_p|}{|\rho_s|} = \tan\{\Psi\} . \quad (60)$$

In the case of heterodyne interferometry, the reference arm phase is continuously varied to create a Doppler shift. This creates an interference pattern that is modulated at the difference in frequency between the two arms. The phase and amplitude of this signal can be monitored via lock in amplifiers. The interference patterns using heterodyne interferometry are given by:

$$\begin{aligned} I_s &= I_o + I_s + 2|A_o||\rho_s|\cos(\Phi_o - \Phi_s + \Omega t) \\ I_p &= I_o + I_p + 2|A_o||\rho_p|\cos(\Phi_o - \Phi_p + \Omega t) \end{aligned} , \quad (61)$$

where Ω is the frequency difference between the two arms of the interferometer. The interference pattern has a time dependant component in the cross term. The Doppler shift is typically in the MHz range (radio frequency), and electronic components can monitor the phase and intensity of the signal. The heterodyned signal is:

$$\begin{aligned} I_s &= 2|A_o||\rho_s|\cos(\Phi_o - \Phi_s + \Omega t) \\ I_p &= 2|A_o||\rho_p|\cos(\Phi_o - \Phi_p + \Omega t) \end{aligned} . \quad (62)$$

The difference between the S and P phases yields Δ :

$$Phase_s - Phase_p = (\Phi_o - \Phi_s) - (\Phi_o - \Phi_p) = \Phi_p - \Phi_s = \Delta . \quad (63)$$

Ψ is measured via the time average of the S and P channels:

$$\frac{\langle I_p \rangle}{\langle I_s \rangle} = \frac{2|A_o||\rho_p|}{2|A_o||\rho_s|} = \frac{|\rho_p|}{|\rho_s|} = \tan\{\Psi\}. \quad (64)$$

The technique of interference with a common reference has been explained in a mathematical manner. Polarized light at 45°, is an essential component to these interferometers and provides an unbiased reference for the interference.

DMITRIEV INTERFEROMETRIC ELLIPSOMETER

The first known paper on interferometric ellipsometry appeared in 1972 (Dmitriev 1972).

Dmitriev's instrument consists of a modified Mach-Zehnder interferometer as shown in

Figure 9.

Figure 9 The interferometric ellipsometer developed by Dmitriev

The source light is polarized at 45° , providing an unbiased reference wave. The beam transmits through the sample before entering a Mach-Zehnder interferometer. In the test arm of the interferometer, the beam travels unaltered through the first beam splitter until it is split into two beams by a non-polarizing beam splitter.

The reference arm is reflected by the first beam splitter and then intersects a circular polarizer (polarizer and quarter-wave plate at 45° combination). The purpose of this circular polarizer is to control the intensity of the reference beam. (Note: The circular polarizer is purely for intensity control and is not otherwise an essential component in the design.) The circularly polarized beam is transmitted by another beam splitter before being reflected by a mirror mounted on a piezo-electric transducer.

The PZT is translated in a continuous fashion to Doppler shift the reference beam with respect to the test beam. The Doppler shifted beam is reflected by the beam splitter before encountering a polarizer oriented at 45° to the plane of the optical beam. This generates a polarization reference source immediately prior to the final. This polarizer is essential to the proper operation of the instrument

A non-polarizing 50% -50% beam splitter brings the test and reference beams together and interference occurs. Two interference patterns are directed to two photo-multiplier tubes preceded by linear polarizers. One beam has a polarizer oriented at 0° while the other has a polarizer oriented at 90° . The combination of the beam splitter and the two

polarizers act as a polarization beam splitter, much like a Wollaston, or beam splitting Glan-Thompson prism. Therefore, the detectors are sampling the S and P components of the interference pattern, generated by interference of the test and reference beam.

Each interference pattern is a superposition of the test and reference beams for the given polarization component. The S component of the test beam contains the S transmittance and phase change of the sample. By the same token, the P transmittance and phase change is encoded into the P component of the test beam. The reference beam has identical amplitudes and phases for both polarizations.

Ignoring the phase change on reflection effects of the beam splitters and mirrors the reference beam has the following Jones matrix:

$$E_{reference} = \begin{bmatrix} |A_o| e^{i\Phi_o} \\ |A_o| e^{i\Phi_o} \end{bmatrix} = A_o e^{i\Phi_o} \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad (65)$$

The interference patterns generated at the PMT's are:

$$\begin{aligned} I_s &= I_o + I_s + 2|A_o||\rho_s| \cos(\Phi_o - \Phi_{TA} - \Phi_s + \Omega t) \\ I_p &= I_o + I_p + 2|A_o||\rho_p| \cos(\Phi_o - \Phi_{TA} - \Phi_p + \Omega t) \end{aligned} \quad (66)$$

where the reference arm amplitude $|A_o|$ is a variable set by the operator of the instrument and Φ_{TA} is the polarization-independent phase difference between the test arm and reference arm. The measured phase of the two interference patterns is:

$$\begin{aligned} Phase_s &= (\Phi_o - \Phi_{TA} - \Phi_s) \\ Phase_p &= (\Phi_o - \Phi_{TA} - \Phi_p) \end{aligned} \quad (67)$$

The difference between the S and P phase measures the ellipsometric parameter Δ :

$$Phase_s - Phase_p = \Phi_p - \Phi_s = \Delta. \quad (68)$$

Ψ is measured via the time average of the S and P channels:

$$\frac{\langle I_p \rangle}{\langle I_s \rangle} = \frac{2|A_o||\rho_p|}{2|A_o||\rho_s|} = \frac{\rho_p}{\rho_s} = \tan\{\Psi\}. \quad (69)$$

The Dmitriev ellipsometer uses the AC component of the interference pattern to measure Ψ while the phase difference between the two interferograms yields Δ . Some of the advantages of this instrument include the speed at which it can operate. Heterodyne interferometry typically operates in the MHz range, far exceeding any speed available with conventional ellipsometry. The only moving parts are solid state PZT's. This instrument can operate at any wavelength where coherent sources, detectors, beam splitters and polarizers can be procured. The literature available on Dmitriev's experiment does not indicate any measurement accuracy.

Dmitriev's instrument provides a measurement of the state of polarization at a single point and cannot be used for imaging ellipsometry because of the data acquisition technique. Two-dimensional CCD arrays cannot be used for heterodyne interferometry because they are too slow and cannot be synchronized to a heterodyned signal.

A modern rendition of the instrument was provided by Calvani et al. (Calvani et al 1986, 1991). The impetus of their work was to measure the state of polarization of light exiting optical fibers under the presence of stress and environmental effects. The layouts presented by Calvani et. al. use the same measurement principles of mixing the beam to be measured with a frequency-shifted beam linearly polarized at 45° . An acousto-optic modulator provides the Doppler frequency shift.

Calvani et. al. propose the use of two instruments, one, where the sample under test is external to the Mach-Zehnder interferometer and an instrument with the sample under test is placed in the test arm of the interferometer. The mathematics of both instruments are identical to that already presented and will not be repeated. They both involve interference between a reference wave polarized at 45° and a test wave that is elliptically polarized.

The first instrument is identical to Dmitriev's except that the sample is a fiber. A layout of this instrument is found in Figure 10. The instrument is intended to measure the state of polarization of light exiting a fiber. The laser used as a source is polarized at 45° . An acousto-optic modulator that also serves as a beam splitter provides the Doppler shift. A Soleil-Babinet compensator is placed after the polarizer in the reference arm to remove polarization-dependant phase effects in the instrument (i.e. phase change on reflection from mirrors and beam splitters).

Figure 10 Calvani et. al. (1986) Interferometric ellipsometer with sample external to interferometer

The two polarization components are directed to two detectors by a beam splitting Glan-Thompson polarizer. The polarization ellipse is directly observable on an oscilloscope and the polarization data is acquired via lock in amplifiers. A stress device is attached to the fiber to study the effects of fiber stress on the polarization state of the output light.

The layout in Figure 11 illustrates the use of placing a sample directly within the test arm of the interferometer. The laser is polarized at 45° and the reference arm remains polarized at 45° . The test arm state of polarization is altered via interaction with the fiber.

The mathematics of the interference pattern is identical to the case where the sample is external to the interferometer.

Figure 11 Calvani et. al. (1991) Interferometric ellipsometer with sample contained in one arm of interferometer

The unique feature of this instrument is the fact that the sample under test is placed directly within one arm of the interferometer. The measurement speed is superior to conventional ellipsometry and no compensators are required to make the measurements. They claim a measurement noise of 0.05db for the ratio of amplitudes and 0.1 degree of phase (Calvani et al 1986). Neither of the instruments presented by Calvani et al are configured for performing imaging ellipsometry.

Lin et al (Lin et al 1989) constructed an interferometric ellipsometer in a Mach-Zehnder configuration specifically designed for reflection ellipsometry. Heterodyne

The advantages of this instrument include that there are no polarizing components within the interferometer. Variable angle of incidence ellipsometry can be performed without realignment of the entire instrument. Absolute calibration is possible via insertion of a mirror prior to the sample. The authors claim an accuracy of 1% via comparison of measurements made with a commercial ellipsometer, but no repeatability data is provided. Because there are multiple reflections from the sample this instrument does not allow for imaging ellipsometry

HAZEBROEK AND HOLSCHER INTERFEROMETRIC ELLIPSOMETER

Hazebroek and Holscher (Hazebroek et al. 1973, 1983) developed an interferometric ellipsometer based on a Michelson interferometer arrangement. Figure 13 illustrates the layout of the instrument. A laser is used as the source and is followed by a polarizer at 45°. A non-polarizing beam splitter splits the beam into a test and reference arm.

Figure 13 The Hazebroek and Holscher Interferometric Ellipsometer

The test beam reflects off the sample twice in this configuration yielding a Jones matrix that is slightly different from the previous instruments:

$$E_{test} = \begin{bmatrix} |\rho_s|^2 e^{i2\Phi_s} \\ |\rho_p|^2 e^{i2\Phi_p} \end{bmatrix}. \quad (70)$$

The reference arm beam is transmitted by the beam splitter before reflection by a corner cube reflector mounted on an electro-magnetic driver. The movement of the corner cube causes a Doppler shift between the two arms of the interferometer, facilitating heterodyne interferometry. The corner cube was selected so that small angular orientation changes in the cube during the scan have a minimal effect on the measurement.

The beams are recombined by the beam splitter and pass through a Wollaston prism so the S and P components can be detected individually. The S (or P) interference pattern is a

coherent superposition between the S (or P) component from the test arm and the S (or P) component from the reference arm. Because the reference arm is a linearly polarized beam at 45°, the two interference patterns share a common reference.

Heterodyne interferometry is used to acquire the phase and magnitude of the interfered waves. The interference patterns are:

$$E = E_{test} + E_{reference} = |A_o|e^{i\Phi_o + \Omega t} \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} |\rho_s|^2 e^{i2\Phi_s} \\ |\rho_p|^2 e^{i2\Phi_p} \end{bmatrix} = \begin{bmatrix} |A_o|e^{i\Phi_o + \Omega t} + |\rho_s|^2 e^{i2\Phi_s} \\ |A_o|e^{i\Phi_o + \Omega t} + |\rho_p|^2 e^{i2\Phi_p} \end{bmatrix}, \text{ and} \quad (71)$$

$$I = \begin{bmatrix} I_o + I_s + 2|A_o||\rho_s|^2 \cos(\Phi_o - 2\Phi_s + \Omega t) \\ I_o + I_p + 2|A_o||\rho_p|^2 \cos(\Phi_o - 2\Phi_p + \Omega t) \end{bmatrix}.$$

The ellipsometric parameters are determined via a difference in phase between the two polarizations and the amplitude of the heterodyned signal:

$$Phase_s - Phase_p = 2\Phi_p - 2\Phi_s = 2\Delta, \text{ and} \quad (72)$$

$$\frac{\langle I_p \rangle}{\langle I_s \rangle} = \frac{2|A_o||\rho_p|^2}{2|A_o||\rho_s|^2} = \frac{|\rho_p|^2}{|\rho_s|^2} = \tan^2\{\Psi\}. \quad (73)$$

When a return mirror is inserted in the test arm of the interferometer before the sample, all effects of the sample are removed. An absolute calibration can be performed which removes the effects of the beam splitter and corner cube reflector. The authors claim this allows for absolute measurements of the ellipsometric parameters because errors due to system imperfections are removed once compared with this reference situation.

The authors (Hazebroek et al 1973, 1983) claim many advantages of the system including that no compensator is required, absolute measurements are possible, and the polarization ellipse is directly observable on an oscilloscope. Only one other component needs repositioning to perform multiple angle of incidence ellipsometry. The alignment of the instrument for different angles of incidence is easily performed and is controlled to interferometric tolerances. Their measurements were made in 30ms intervals allowing for the visualization of dynamic film growth. In their initial work, the authors claim an accuracy of “a few hundredths of a degree” from analysis of the system (not an experimental repeatability). The authors claim that any orientation error of the initial polarizer or phase change on reflection effects from the beam splitter is compensated by the calibration technique.

A paper by Wind and Hemmes (1994) describing improvements to the Hazebroek and Holscher system, indicates that the instrument constructed by Hazebroek and Holscher was only able to take a full set of ellipsometric data every 8 seconds. In addition, they claim that “considerable averaging of the signals is required to remove fluctuations,” and “the algorithm used for retrieving the ellipsometric data from the sine waves is very time-consuming.”

Wind and Hemmes (1994) showed that it is possible to improve the Hazebroek and Holscher interferometer through the use of a Zeeman two-frequency laser. A Zeeman laser produces two collinear beams from a single laser source. These two beams differ in

two ways. They differ slightly in wavelength ($\omega_1 - \omega_2 = \text{approximately } 1\text{MHz}$) and have opposite circular polarizations. The combination of a Zeeman laser and a quarter-wave plate at 45° produces the following beam:

$$E_{Zeeman} = A_o e^{i\omega_o t} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + A_o e^{i\omega_o t} \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (74)$$

Wind and Hemmes developed the arrangement shown in Figure 14 below.

Figure 14 Wind and Hemmes (1994) Interferometric ellipsometer.

A quarter-wave plate and a polarizing beam splitter send the frequencies into different arms of the interferometer. The reference beam passes through a polarizer oriented at 45° before being recombined with the test beam. The test beam is polarized at 45° before a double reflection from the sample.

Interference occurs when the non-polarizing beam splitter brings the test and reference beams together. Although the arrangement is different, the mathematics is identical to the Hazebroek and Holscher experiment and will not be repeated.

A later paper Hemmes et. al. (1998) discusses the results obtained with a system built in this configuration. The optical response of a LCD, Pockels cell and an electro-chemical reaction were studied. Data acquisition was accomplished via a digital oscilloscope. A response time of 1microsecond was demonstrated which consisted of 100 samples from the digital oscilloscope. The authors report that “a relative accuracy of 0.15° in Δ and Ψ could be obtained at a time resolution of 1microsecond.” Considering that this instrument was an improvement over the earlier work of Hazebroek and Holscher, the accuracy claimed in the early work is somewhat suspect.

The main advantage of this new arrangement over the work of Hazebroek and Holscher is that the moving corner cube has been eliminated from the system. Once again, the measurements are non-imaging and not extendable to two dimensions.

CONCLUSION

Interferometric ellipsometers are a distinct class of ellipsometers, more similar to polarization interferometers than a classical ellipsometer. They use one of two techniques to obtain the ellipsometric parameters. Direct interference between the two

components or interference of each polarization component with a common reference. This common reference is a beam linearly polarized at 45° .

They offer some distinct advantages over the conventional nulling PCSA ellipsometer. The visualization of fast surface processes is possible with the use of heterodyne interferometry. The elimination of moving parts greatly simplifies the mechanical design. Most of these instruments do not require a compensator, thereby extending the possible wavelength range of ellipsometers since only polarizers and beam splitters are required. Alignment of the systems is accomplished with interferometric accuracy.

Disadvantages include the fact that they are not all common path, and the possibility of unforeseen errors are possible. Variations in the beam splitter reflectivity and phase change on reflection as a function of position would cause errors. The effects of component imperfection and alignment on the performance of the instruments were not discussed in any of the papers studied. This author believes that the claims of “absolute accuracy” possible with some of the systems (Lin et al, Hazebroek et al) is misleading. Errors in the final polarization beam splitter would not be removed. Interferometric ellipsometers require vibration isolation, which is costly and limits the portability of the instruments.

None of the instruments as presented by the original authors are imaging ellipsometers. Although many of the arrangements could be configured for imaging ellipsometry, the

data acquisition technique of heterodyne interferometry is not applicable to two-dimensional CCD arrays. In addition, some of the instruments have two reflections off the sample that precludes the formation of a single image.

THE PHASE-SHIFTING INTERFEROMETRIC IMAGING ELLIPSOMETER (PSIIE)

Ellipsometers have been characterizing thin-films in science and industry since their invention. Since then, research into novel ellipsometric techniques has continued. Interest in two-dimensional surface characterization spurred research into imaging ellipsometry. Two-dimensional surface characterization became possible with new techniques. Multiple null conditions allowed researchers to characterize smoothly varying films. The technique proved to be of little help for more generalized surfaces or where complete surface data is required. Multiple frame algorithm techniques in conjunction with the classical PCSA ellipsometer provided true two-dimensional surface measurements in a few frames of data. All of these arrangements required actively rotating components for the measurements.

Researchers with expertise in interferometry used the techniques of polarization interferometry to measure the ellipsometric parameters with high accuracy and speed using heterodyne interferometric techniques. The techniques are fast, accurate and repeatable but are not applicable to imaging ellipsometry.

The impetus of the work in this dissertation is to unite the techniques of imaging ellipsometry with the techniques of phase-shifting interferometry in an instrument that performs imaging ellipsometry utilizing phase-shifting ellipsometry as the data

acquisition technique. The phase-shifting interferometric imaging ellipsometer (PSIIE) is the culmination of this work. The theory of the phase-shifting interferometric imaging ellipsometer, its data acquisition technique, results of experimentation, error analysis and the method of calibration for the instrument will be discussed.

CONCEPTUAL DESIGN OF THE PHASE-SHIFTING INTERFEROMETRIC IMAGING ELLIPSOMETER (PSIIE)

Figure 15 illustrates the layout of the phase-shifting interferometric imaging ellipsometer (PSIIE). It consists of a polarized source assembly, a polarization interferometer, imaging optics, a Wollaston prism (analogous to an analyzer) and a CCD array.

Figure 15 Layout of the phase-shifting interferometric imaging Ellipsometer

The polarized source assembly has a laser, spatial filter and collimator followed by a polarizer oriented at 45°. The polarizer, referred to as polarizer 1, generates a linearly polarized beam oriented at 45°. As discussed previously, a linearly polarized beam has

no phase difference between the S and P components and identical amplitudes. The following Jones matrix represents the electric field of the light leaving polarizer 1:

$$E_{Source} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad (75)$$

where the constant term $\sqrt{2}/2$ has been dropped for clarity.

The PSIIE as illustrated in Figure 15 has an angle of incidence on the sample of 45° but can be operated so that the angle of incidence on the sample is between 15° and 70° . The beam reflected from the surface becomes elliptically polarized from the non-normal incidence reflection from the sample. Following reflection from the sample the electric field is represented by:

$$\begin{aligned} E_{Sample}(x, y) &= J_{sample}(x, y) E_{Source} = \\ &= \begin{bmatrix} \rho_s(x, y) & 0 \\ 0 & \rho_p(x, y) \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \rho_s(x, y) \\ \rho_p(x, y) \end{bmatrix} = \begin{bmatrix} |\rho_s(x, y)| e^{i\Phi_s(x, y)} \\ |\rho_p(x, y)| e^{i\Phi_p(x, y)} \end{bmatrix}, \quad (76) \end{aligned}$$

where $\rho_p = |\rho_p| e^{i\Phi_p}$ and $\rho_s = |\rho_s| e^{i\Phi_s}$ are the amplitude reflection coefficients for the sample. This matrix contains all the information necessary to calculate the two ellipsometric parameters.

The sample amplitude reflection coefficients are a function of position on the sample. In order to simplify the derivation of the instrument, the spatial dependence of the reflection coefficients is neglected in some of the equations. In this case, the derivation can be

thought of as a derivation for a given object point and is applicable to the entire field of the sample on a point by point basis. Some equations will contain the spatial dependence to remind the reader of the two dimensional nature of the instrument.

To review, the ellipsometric parameters Δ and Ψ are defined in terms of the complex amplitude reflection coefficients for the S and P components as shown in Equation (77):

$$\rho = \frac{\rho_p}{\rho_s} = \frac{|\rho_p|}{|\rho_s|} e^{i(\Phi_p - \Phi_s)} = \tan\Psi e^{i\Delta}. \quad (77)$$

Following reflection from the sample, the light enters a modified Michelson Interferometer. There are two arms to this interferometer, the “Polarization Test Arm” and the “Polarization Reference Arm”. These are so named to be analogous to the test and reference arm of a Twyman Green Interferometer. The meanings of “Polarization Test Arm” and “Polarization Reference Arm” will become clear.

A non-polarizing 50%/50% beam splitter is used in the PSIIE. It is designed to equally reflect and transmit all light independent of polarization state with an intensity reflection or transmission coefficient of 50%. Therefore, 50% of each components intensity will be reflected into the polarization reference arm and 50% of each components intensity will be transmitted into the polarization test arm. For this beam splitter to be ideal, the phase change on reflection or transmission through the beam splitter should be identical for the two components.

Ideal 50%/50% beam splitters do not exist. Commercially available beam splitters do not exhibit perfect performance. While their reflectance and transmittance can be close to 50%, there is invariably a small error in reflectance and a phase change on reflection for each polarization component because of the thin-film nature of the beam splitter. Therefore, the beam splitter introduces both phase and amplitude effects on the beams, thereby changing the polarization state.

To summarize the results of the error analysis to be presented later in this document, the beam splitter phase change on reflection causes a constant offset in the Δ measurement. The polarization-dependent amplitude reflectances cause a scale change in the ratio of reflectance measurement. Both of these effects are sample independent and can therefore be removed from the measurement via calibration. In other words, without proper calibration of the beam splitter effects, measurements of Δ and the tangent of Ψ will have static offsets. These effects will be dealt in detail later. To gather a better understanding of the basic operating principals of the instrument, the effects of the beam splitter will be neglected at this time.

POLARIZATION TEST ARM

The beam transmitted through the beam splitter constitutes the “Polarization Test Arm”. This beam retains the polarization ellipse information encoded into the polarization state of the beam following reflection from the sample. After transmission through the beam splitter, the beam is reflected from the polarization test arm return mirror and is reflected by the beam splitter.

From the moment the beams are spatially separated until the moment they are recombined they encounter different optical paths and by definition different optical phases. These phases can be grouped into two spatially dependent terms $\Phi_{RA}(x, y)$ and $\Phi_{TA}(x, y)$, one for each arm of the interferometer. These terms represent the component imperfections and the tilt between the reference and test arms. These component imperfections are polarization-independent and are removable from the Jones matrix. Once again the spatial dependence of these quantities is neglected in some equations for clarity.

The mirror in the polarization test arm is mounted on a PZT actuator that is used to perform phase-shifting interferometry. Φ_{PSI} represents the phase introduced by the PZT. When measuring the phase of an interferogram, there is always an ambiguous piston phase term due to the unknown starting phase of the interferometer.

The electric field from the test arm that reflects from the beam splitter towards the imaging optics is given by:

$$\begin{aligned}
 E_{Test\ Arm} &= J_{Test\ Arm\ Phase} J_{BS-R} J_{BS-T} E_{Sample} \\
 &= e^{i\Phi_{T,1}} e^{i\Phi_{PSI}} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{bmatrix}, \\
 &= \frac{1}{2} \begin{bmatrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{bmatrix} e^{i\Phi_{T,1}} e^{i\Phi_{PSI}}
 \end{aligned} \tag{78}$$

where $J_{\text{Test Arm Phase}}$, J_{BS-R} , and J_{BS-T} refer to the Jones matrix for the test arm phase, beam splitter reflection and beam splitter transmission respectively. All three terms are treated as polarization and spatially independent quantities. The beam splitter effects and the phase introduced by the PZT are considered to be spatially independent as well. On the other hand, the phase due to component imperfections $\Phi_{TA}(x, y)$ and $\Phi_{RA}(x, y)$, and the complex amplitude of the sample reflectance are spatially dependent.

A few conclusions should be noted about Equation (78). The state of polarization of this beam is identical to Equation (76). Although the absolute phase of the wavefront has changed due to the wavefront phase of the test arm, $\Phi_{TA}(x, y)$, the difference in phase between the S and P components remains the same. Although the magnitudes of the beam have been modified, the ratio of the magnitudes in the S and P direction remains the same. Because the beam from this arm of the interferometer has the same state of polarization as the beam reflected from the sample, it is referred to as the polarization test arm.

POLARIZATION REFERENCE ARM

For the techniques of interferometry to be useful for the characterization of the polarization ellipse, i.e. ellipsometry, an arrangement must be developed in which a fringe pattern represents the state of polarization of light or can be converted into it. Characterization of the polarization ellipse using interferometry usually involves one of

two techniques. The first of these is to directly interfere the two polarizations with each other. The second is to interfere each individual polarization with a common reference beam, resulting in two interference patterns, one for each polarization.

The PSIIE utilizes the technique of interference with a common reference. It has already been discussed that the ideal polarization reference is a linearly polarized beam oriented at 45° . In order to accomplish this, the polarization reference arm has a linear polarizer (polarizer 2) oriented at 45° placed between the beam splitter and the return mirror.

The polarization reference arm takes the elliptically polarized beam coming from the sample and “generates” an ideal polarization reference via transmission through a polarizer. This beam transmits through the beam splitter and can be represented by:

$$\begin{aligned}
 E_{Reference\ Arm} &= J_{Reference\ Arm\ Phase} J_{BS-T} J_{Polarizer} J_{BS-R} E_{Sample} \\
 &= e^{i\Phi_{T,1}} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{bmatrix} \\
 &= \frac{1}{4} \begin{bmatrix} |\rho_s| e^{i\Phi_s} + |\rho_p| e^{i\Phi_p} \\ |\rho_s| e^{i\Phi_s} + |\rho_p| e^{i\Phi_p} \end{bmatrix} e^{i\Phi_{T,1}} \quad , \quad (79) \\
 &= \frac{1}{2} C_0 \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{i\Phi_{T,1}} = \frac{1}{2} C_0 \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{i\Phi_{T,1} + \Phi_{C_0}}
 \end{aligned}$$

where

$$C_0 = \frac{1}{2} \{ |\rho_s| e^{i\Phi_s} + |\rho_p| e^{i\Phi_p} \} = |C_0| e^{i\Phi_{C_0}} \quad . \quad (80)$$

Because this arm generates a polarization reference wave, it is referred to as the polarization reference arm.

INTERFERENCE BETWEEN THE POLARIZATION REFERENCE AND TEST ARMS

Interference between the two beams occurs when the beam splitter recombines the beams. The interfered beams can be represented by:

$$\begin{aligned}
 E_{Interference} &= E_{Reference\ Arm} + E_{Test\ Arm} \\
 &= \frac{1}{2} \left[\begin{matrix} |\rho_s| e^{i\Phi_s} \\ |\rho_p| e^{i\Phi_p} \end{matrix} \right] e^{i\Phi_{T,1} + \Phi_{PSI}} + \frac{1}{2} |C_0| \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{i\Phi_{R,1} + \Phi_{C_0}} \quad (81) \\
 &= \frac{1}{2} \left[\begin{matrix} |\rho_s| e^{i\Phi_s} e^{i\Phi_{T,1} + \Phi_{PSI}} + |C_0| e^{i\Phi_{R,1} + \Phi_{C_0}} \\ |\rho_p| e^{i\Phi_p} e^{i\Phi_{T,1} + \Phi_{PSI}} + |C_0| e^{i\Phi_{R,1} + \Phi_{C_0}} \end{matrix} \right]
 \end{aligned}$$

Including the spatial dependence of all the terms Equation (81) becomes:

$$\begin{aligned}
 E_{Interference}(x, y) &= E_{Reference\ Arm}(x, y) + E_{Test\ Arm}(x, y) \\
 &= \frac{1}{2} \left[\begin{matrix} |\rho_s(x, y)| e^{i\Phi_s(x, y)} \\ |\rho_p(x, y)| e^{i\Phi_p(x, y)} \end{matrix} \right] e^{i\Phi_{T,1}(x, y) + \Phi_{PSI}} + \frac{1}{2} |C_0(x, y)| \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{i\Phi_{R,1}(x, y) + \Phi_{C_0}} \quad (82) \\
 &= \frac{1}{2} \left[\begin{matrix} |\rho_s(x, y)| e^{i\Phi_s(x, y)} e^{i\Phi_{T,1}(x, y) + \Phi_{PSI}} + |C_0(x, y)| e^{i\Phi_{R,1}(x, y) + \Phi_{C_0}(x, y)} \\ |\rho_p(x, y)| e^{i\Phi_p(x, y)} e^{i\Phi_{T,1}(x, y) + \Phi_{PSI}} + |C_0(x, y)| e^{i\Phi_{R,1}(x, y) + \Phi_{C_0}(x, y)} \end{matrix} \right]
 \end{aligned}$$

Equation (82) represents the superposition of the electric fields from the two beams of the interferometer. The electric fields in the S and P components are quite similar. The phase and amplitude reflection coefficient for the S component are found in the S interference pattern, while the P interference pattern contains the same for the P component. Otherwise the equations are identical.

A lens images the surface under test to a focal plane array. The PSIIE independently samples the interference patterns from the S and P polarization components via a Wollaston prism inserted between the imaging lens and the CCD array. A Wollaston prism separates a beam into two beams according to their polarization state as shown in Figure 16.

Figure 16 Wollaston prism

The Wollaston prism is aligned with the plane of incidence so it splits the S and P polarization components into two distinct and spatially separated interference patterns on the CCD array (see Figure 15). The Wollaston prism generates two identical images of the object on the CCD that have the same magnification. The S and P interference patterns are independently sampled and acquired simultaneously.

Equations (83) and (84) represent the intensity of the two interference patterns:

$$I_p = \frac{1}{4} \left\| \rho_p(x, y) e^{i\Phi_p(x, y) + \Phi_{T,1}(x, y) + \Phi_{PSI}} + C_0(x, y) e^{i\Phi_{R,1}(x, y) + \Phi_{C_0}(x, y)} \right\|^2 \quad \text{and ,} \quad (83)$$

$$I_s = \frac{1}{4} \left\| \rho_s(x, y) e^{i\Phi_s(x, y) + \Phi_{T,1}(x, y) + \Phi_{PSI}} + C_0(x, y) e^{i\Phi_{R,1}(x, y) + \Phi_{C_0}(x, y)} \right\|^2$$

$$\begin{aligned}
I_p &= \frac{1}{4} \left\{ |\rho_p(x, y)|^2 + |C_0(x, y)|^2 + \right. \\
&\quad \left. 2|\rho_p(x, y)||C_0(x, y)| \cos \left\{ \Phi_p(x, y) + \Phi_{TA}(x, y) + \Phi_{PSI} - \Phi_{RA}(x, y) - \Phi_{C_0}(x, y) \right\} \right\} \\
I_s &= \frac{1}{4} \left\{ |\rho_s(x, y)|^2 + |C_0(x, y)|^2 + \right. \\
&\quad \left. 2|\rho_s(x, y)||C_0(x, y)| \cos \left\{ \Phi_s(x, y) + \Phi_{TA}(x, y) + \Phi_{PSI} - \Phi_{RA} - \Phi_{C_0}(x, y) \right\} \right\} . \quad (84)
\end{aligned}$$

The interference patterns contain phase and amplitude information that will be used to calculate the ellipsometric parameters.

PSIIE INTERFEROGRAM PHASE

The phase of the two interferograms contains information about the polarization-independent component imperfections in the interferometer $\Phi_{RA}(x, y)$ and $\Phi_{TA}(x, y)$, as well as the polarization-dependent phase change on reflection of the sample $\Phi_p(x, y)$ and $\Phi_s(x, y)$. Phase-shifting interferometry (Creath 1988) is used to extract the phase of each interferogram.

The absolute phase of the interferogram is not accessible because of an unknown piston term representing the difference in path length of the two arms of the interferometer. Only relative phase on a point by point basis is available when considering either interferogram by itself. The two interferograms are acquired simultaneously and, as a result, the unknown piston term is identical for the two. When the phases of the two

interferograms are spatially co-registered and subtracted on a point by point basis, the resultant difference in phase between the two is independent of the initial phase of the interferometer. This is an important principle of the PSIIE.

For a given location on the sample, there are two images on the CCD. For each location in one interferogram (S component) there is a corresponding location in the other interferogram (P Component) which experienced the same polarization-independent wavefront errors. The only difference between the interference patterns at these locations is their respective electric field directions, the magnitude of the wave and the phase due to the reflection from the sample. In this way, a given location in one interferogram can be considered to be common path with respect to the corresponding location in the other interferogram.

The phases of the two interferograms can be extracted via phase-shifting interferometry yielding the following result:

$$\begin{aligned} P \text{ Phase} &= \{ \Phi_p(x, y) + \Phi_{TA}(x, y) - \Phi_{RA}(x, y) - \Phi_{C_s}(x, y) + \text{Piston Term} \} \\ S \text{ Phase} &= \{ \Phi_s(x, y) + \Phi_{TA}(x, y) - \Phi_{RA}(x, y) - \Phi_{C_0}(x, y) + \text{Piston Term} \} \end{aligned} \quad (85)$$

Examination of Equation (85) and Figure 15 illustrates how the two interferograms can be considered to be common path with respect to each other. All of the polarization-independent phase terms in Equation (85) are identical for the two interferograms. In

order to extract Δ , the two interferograms must be separated, co-registered and subtracted point by point. Equation (86) illustrates how Δ results from this subtraction:

$$\begin{aligned} P \text{ Phase} - S \text{ Phase} &= \\ &= \Phi_p(x, y) + \Phi_{TA}(x, y) - \Phi_{RA}(x, y) - \Phi_{c_0}(x, y) + \text{Piston Term} \\ &- \left\{ \Phi_s(x, y) + \Phi_{TA}(x, y) - \Phi_{RA}(x, y) - \Phi_{c_0}(x, y) + \text{Piston Term} \right\} = . \end{aligned} \quad (86)$$

$$P \text{ Phase} - S \text{ Phase} = \Delta(x, y) = \Phi_p(x, y) - \Phi_s(x, y)$$

Through the above derivation, it has been shown that the PSIIIE can measure the ellipsometric parameter Δ via a subtraction of the phases of the P and S interferograms. Now it will be shown that a closer examination of the amplitude information contained in the two interferograms yields the ellipsometric parameter Ψ .

PSIIIE INTERFEROGRAM FRINGE MODULATION

The intensity distribution (an interference pattern) shown in Equation (84) was used to calculate the ellipsometric parameter Δ through the phase of the interference pattern. The fringe visibility is used to measure the ellipsometric parameter Ψ . The fringe visibility of the interferograms in Equation (84) are:

$$\begin{aligned} V_p &= \frac{2|\rho_p||C_0|}{|\rho_p|^2 + |C_0|^2} = \frac{V_{AC_p}}{V_{DC_p}} \\ V_s &= \frac{2|\rho_s||C_0|}{|\rho_s|^2 + |C_0|^2} = \frac{V_{AC_s}}{V_{DC_s}} \end{aligned} \quad (87)$$

The tangent of Ψ is the ratio of the P to S amplitude reflectance of the surface under test. The ratio of the P to S visibilities does not yield this because the denominators do not cancel properly. The ratio of the AC component of the visibilities yields the correct result:

$$\frac{AC_{V_P}}{AC_{V_S}} = \frac{2|\rho_P||C_0|}{2|\rho_S||C_0|} = \frac{|\rho_P|}{|\rho_S|} = \tan\Psi \quad . \quad (88)$$

Therefore, through the AC component of the visibility of the S and P interference patterns, the ellipsometric parameter Ψ can be determined.

COMPONENTS USED IN PSIIIE

The layout shown in Figure 15 is used for all experimentation. The source is a Spectra Physics 10mw HeNe laser, spatially filtered and collimated to a beam size of 25mm. Attenuation is accomplished via neutral density filters and crossed polarizers. The collimating lens has a focal length of 115mm and is uncoated. The two polarizers in the system are from Meadowlark Optics. The polarizing material is dichroic HN42HE Polaroid epoxied between optically polished plates of Fused silica. The outer surfaces of the fused silica are broad band AR coated reducing the reflectance to under 1%. The beam splitter is a 12mm x 12mm path matched beam splitter from Karl-Lambrecht. Its coating is also broad band. The Wollaston prism, on loan from Karl Lambrecht, has a divergence angle of 2deg and is uncoated. The imaging lens has a focal length of 135mm and is uncoated. Burliegh makes the PZT. The WYKO Corporation provided the software, electronics and optics used in the PSIIIE.

The mounts for the two polarizers are from Newport Corporation and have a resolution of 0.5° . The mount for the Wollaston prism has a resolution of 0.25° .

The Cohu camera has 768×494 pixels with a $9\mu\text{m}$ pixel size. The frame grabber samples the analog signal from the camera and outputs an 8bit digital signal with 512×480 pixels. The measurement software takes every other row and column and outputs the phase and modulation data in 256×240 pixels. The magnification of the object onto the CCD is approximately $1 / 2.75$ providing a resolution in object space of 25 microns per pixel if all pixels are used for acquisition. Because of the re-sampling of the frame grabber and the fact that every other row and column are sampled the final resolution of a pixel is approximately $63\mu\text{m}$ in object space ($23\mu\text{m}$ in image space).

The numerical aperture of the system in image space is 0.027. The diffraction limited resolution of the optical system in image space is therefore $35\mu\text{m}$. The equivalent resolution in object space per resampled pixel is 100 microns. An area of $5\text{mm} \times 9\text{mm}$ is evaluated in each measurement in a resolution of 80×140 .

To summarize, the PSIIE measures an area of $5\text{mm} \times 9\text{mm}$ in 80×140 pixels providing a resolution of $63\mu\text{m}$ with 8-bit resolution. Unfortunately many of the optical components used in the PSIIE are either not coated or are broad band coated.

POLARIZING COMPONENT ROTATIONAL ORIENTATION CALIBRATION TECHNIQUES

Operation of any ellipsometer requires a calibration procedure. Proper performance will only be obtained when the instrument is calibrated. Error analysis indicates that the polarizing components must be oriented properly. This section details the procedure used to orient the polarizing components.

The phase-shifting interferometric imaging ellipsometer contains three polarizing components. The orientation of these components around the optical axis is critical to the proper operation of the instrument. Two techniques have been developed to accomplish this. One calibrates the orientations of polarizers 1 and 2 while the second calibrates the Wollaston prism.

Error analysis indicates that the orientation of polarizers 1 and 2 causes predictable errors in the ratio of reflectance measurement. For calibration of the instrument this is a benefit because you get a predictable error versus the orientation of the element. The calibration technique for polarizers 1 and 2 takes advantage of the fact that the *PSIIE* can operate with them oriented at 45° or 135° . The measured ratio of reflectances should be identical when measured at 45° or 135° , but the functional form of the errors around these two locations is different. This difference is used to calibrate their rotational orientation.

Figure 17 illustrates the functional form of the error in the ratio of reflectance measurement near 45 and 135°. The measured ratio of reflectance is the same in both plots when the polarizer is correctly oriented. This is the basis of the calibration technique.

Figure 17 Error in ratio of reflectance characterization versus angular orientation of polarizer 1 or 2.

Figure 18 illustrates the measured calibration data using this technique. Six measurements in 2° increments were taken from 42°-52° and 132°-142° in each case. This located the proper orientation to well within the 0.5° precision of the mounts. The proper orientations were determined to be 47.3° and 44.5°.

Figure 18 Results of calibration technique for polarizer 1 and 2

Developing a calibration technique for the Wollaston prism is more difficult. The technique used involves the measurement of a Soleil-Babinet compensator (SBC). A SBC is a variable retardance device. The amount of retardance can be varied via a micrometer screw. Because it's a pure retarder, the transmission of both polarizations is the same. When aligned along either the fast or slow axis, the measurement of a SBC will yield a Δ measurement equal to the phase retardance but the ratio of reflectance measurement should always be one since the transmission is equal for the two axes.

When the Wollaston prism is not oriented correctly, errors in the measurements are present. The errors in the phase are not of interest for this calibration procedure. The errors in modulation are interesting and yield a calibration technique. Figure 19 illustrates the error in the ratio of reflectance for a -1° , -0.5° , 0.5° and 1° orientation error. The plots illustrate the error in modulation expressed as a ratio versus the phase of the SBC. The upper most curve is the -1° curve and the others follow in order. There is no error (scale error = 1) at 180° and the error reaches a maximum of $\pm 7\%$ at 0° .

Figure 19 Scale error in ratio of reflection versus phase of SBC for a ± 1 and $\pm 0.5^\circ$ error in the orientation of the Wollaston Prism

This phenomenon provides a method of calibration because the slope of the curve changes from positive to negative when the Wollaston prism orientation error changes sign. The calibration technique involves taking a series of measurements with different prism orientations and different SBC retardances. When the measured modulation is flat versus the SBC retardance, the Wollaston prism is oriented correctly.

Figure 20 illustrates the measured data from a calibration run of the Wollaston prism. Three Soleil-Babinet Compensator retardances were measured at five different Wollaston prism orientations. Between 0.5° and 1° the slope of the measured modulation changes from positive to negative. This indicates that the correct orientation lies between them. Subsequent measurements confirmed this.

Figure 20 Calibration data for Wollaston Prism

Two calibration techniques were developed to orient the polarizing components in the phase-shifting interferometric imaging ellipsometer. Both of these take advantage of the

systematic errors that improper orientations cause in the measurements. These errors are detrimental to the measurement process but can be used advantageously in a calibration procedure. By rotating polarizers 1 and 2 and looking at the measured modulation near 45° and 135° , the proper orientation of the two polarizers can be determined. Calibration of the Wollaston prism is accomplished via the measurement of a Soleil-Babinet compensator at different retardances and prism orientations.

COMMENTS

It has been demonstrated through the use of Jones Matrices and physical arguments that the phase-shifting interferometric imaging Ellipsometer measures the ellipsometric parameters of a two dimensional object. The basic technique used in the PSIIE is the interference of each polarization with a common reference wave polarized at 45° . This is done through the placement of a polarizer oriented at 45° in the polarization reference arm a modified Michelson interferometer. The PSIIE is a polarization interferometer configured to measure the state of polarization of an elliptically polarized input beam.

The ellipsometric parameter Δ is measured via the difference in phase between the S and P interferograms while Ψ is measured through the AC component of the interferogram modulations.

This document will detail the error analysis performed on the instrument and present the measurements taken with the PSIIE. A conclusion will examine the unique characteristics, advantages and disadvantages of the instrument.

ERROR ANALYSIS

This section will discuss and quantify the measurement errors caused by improper angular orientation of polarizers 1 and 2 as well as the Wollaston prism. Imperfections in the polarizers will be examined. The reflectance and phase change on reflection effects from the beam splitter will also be discussed. Finally the effects of improper phase-shifting, spurious fringes and vibration will be discussed.

POLARIZING COMPONENT ANGULAR ORIENTATION ERRORS

The PSIIE is a polarization interferometer containing two transmission polarizers and one polarizing beam splitter (Wollaston prism). The two polarizers are aligned at 45° to the plane of incidence while the Wollaston prism is aligned at 0° . Proper operation of the instrument requires accurate alignment of the polarization components. Improper alignment causes errors in the measurement of phase and modulation. The orientation of the polarizing components is not a trivial task and requires a calibration procedure. Perfect angular alignment of the polarizing components is a difficult task and some error in their orientation will always exist.

It will be shown that improper orientation of the two polarizers in the system causes errors in the measurement of the ratio of reflectance but does not affect the measurement of Δ . The orientation of the Wollaston prism on the other hand affects both the modulation and the phase measurements.

All linear polarizers used in the system are made of dichroic HN42HE manufactured by Polaroid. The polarizing material is epoxied between optically polished plates of Fused silica. The outer surfaces of the fused silica are broad band AR coated reducing the reflectance to less than 1%. The extinction ratio of these elements is greater than 1000:1. When illuminated by a coherent laser source, spurious fringes from the faces of the fused silica, and the intermediate Polaroid/epoxy/fused silica interfaces are clearly evident.

POLARIZER 1 ANGULAR ORIENTATION ERROR ANALYSIS

Polarizer number 1 is used to illuminate the sample with light polarized at 45° . It serves to create an illuminating beam that has identical phase and amplitude for the S and P polarizations.

The mounts used in the PSIIE are of fair quality. When considering the precision of the mounts, and the ability to calibrate its orientation, the angular orientation of an element can only be determined to approximately $\pm 0.5^\circ$. Polarizer 1 serves as the input polarizer for the system. Improper orientation of polarizer 1 affects the relative intensities in the two polarizations according to Equation (89) but does not change the

relative phases between the beams. The Jones vector for a beam polarized at an angle theta is given by:

$$\begin{bmatrix} E_s \\ E_p \end{bmatrix} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix}. \quad (89)$$

In the ideal case, where theta equals 45°, half of the light is in each polarization. In the case of a misalignment, this 50-50 situation is perturbed but the relative phase between the two components is not affected. Therefore, from a conceptual point of view, improper orientation of polarizer 1 changes the relative magnitudes of the two polarizations but does not affect the phase of the beam. The measurement of the ratio of reflectances is affected while the phase change on reflection is not.

A complete system analysis is performed in Mathematica that accounts for most system parameters including polarizer orientation. Using ideal system parameters, the correct performance is calculated. Following this, the orientation of the components is modified and the performance of the system under perturbed circumstances is calculated.

For Δ , plots of the difference between the perturbed and ideal phase are calculated and have units of degrees. In the case of the ratio of reflection, it has been found that the errors in general appear to scale linearly with the ratio of reflection. In other words the errors cause a uniform scale factor to be applied to the measured modulation. Therefore, in the case of the ratio of modulation, the ratio of the perturbed to ideal is calculated.

The analysis indicates that the angular orientation of polarizer 1 does not affect the measured phase but does scale the modulation according to Equation (90),

$$\frac{Perturbed}{Ideal} = Tan[\theta_p] . \quad (90)$$

Figure 21 illustrates the scale error that occurs from an improper orientation of polarizer 1. The plot represents the percentage change in ratio of reflectance versus angular orientation error. For example a $\pm 0.5^\circ$ error causes an uncertainty in the modulation of $\pm 1.7\%$. Given the limitations of the mounts being used, this level of uncertainty is expected.

Figure 21 Percentage change in Modulation versus polarizer 1 or polarizer 2 orientation error in degrees

POLARIZER 2 ANGULAR ORIENTATION ERROR ANALYSIS

The situation for polarizer 2 is similar to that of polarizer 1. Polarizer 2 creates a polarization reference wave polarized wave at 45° . Except for some scaling terms the Jones vector for this beam is also given by Equation (89) with the proper orientation being $\theta = 45^\circ$. Once again, it is intuitive that an improper orientation of this polarizer will only affect the relative intensities in the two axes and not the relative phase between them. It is logical to assume that the orientation of this polarizer will only affect the ratio of reflectance measurement, not the phase change on reflection.

Analysis by Mathematica confirms this hypothesis. Improper orientation of polarizer 2 does not affect the phase measurement but does cause a scale change in the ratio of reflectance. A first order derivation of this error indicates that the error also follows the functional form of Equation (90) and the percentage change in ratio of reflectance as a function of angular orientation error is give by Figure 21. Analysis in Mathematica confirms this analysis. Therefore, given a mount position uncertainty of $\pm 0.5^\circ$, the modulation error due to polarizer 2 is $\pm 1.7\%$.

WOLLASTON PRISM ANGULAR ORIENTATION ERROR ANALYSIS

The polarization beam splitter is a Wollaston prism and should be aligned at 0° with respect to the plane of incidence. The Wollaston prism allows the two polarization

components to be independently sampled. Improper orientation of this element causes improper mixing of the two polarizations in the final interferograms.

Simple analysis of the effects of improper orientation of the Wollaston prism is not possible and a closed form for the errors cannot be found. Analysis indicates that the errors caused by an improper orientation of the Wollaston prism affect both the phase and modulation of the interferograms in a non-trivial manner. That is to say, it does not cause a simple constant, linear or scalar error.

Mathematica is used to analyze the effect of these orientation errors. In order to get a better feel for its effects, the errors caused by the Wollaston prism on the phase and modulation will be plotted for all of the samples examined. Each figure has two plots. The first is a plot of the error in the phase change on reflection measurement versus angle of incidence on the sample. The units are degrees of phase retardance error. The second plot is the ratio of the perturbed to ideal ratio of reflectance. This plot is a ratio and therefore has no units.

Figure 22, Figure 23 and Figure 24 detail the error in phase and modulation for a 1° orientation error of the Wollaston prism.

Figure 22 Errors in phase and modulation for silicon substrate measurement as a function of angle of incidence caused by a 1° angular orientation error in the Wollaston prism

Figure 23 Errors in phase and modulation for 51nm SiO₂ film measurement as a function of angle of incidence caused by a 1° angular orientation error in the Wollaston prism

Figure 24 Errors in phase and modulation for silicon substrate measurement as a function of angle of incidence caused by a 1° angular orientation error in the Wollaston prism

It is difficult to see any general trend in this analysis. The mathematics of the process is complicated and the results are non-trivial. The errors must be evaluated on a case by case basis. Table 1 summarizes the results of the errors in the phase measurement. It should be noted that the errors due to the Wollaston prism do scale linearly with the angular error for small angular errors. Therefore, the error for 1° of improper orientation is twice that for 0.5° .

<u>1 Degree Error</u>			
	Substrate	51nm SiO ₂	126nm SiO ₂
Average Error	-0.152	-0.994	0.825
P/V Error	0.770	1.611	2.126
All quantities in Degrees			
<u>0.5 Degree Error</u>			
	Substrate	51nm SiO ₂	126nm SiO ₂
Average Error	-0.076	-0.497	0.413
P/V Error	0.385	0.806	1.063

Table 1 Summary of the results for the phase change on reflection errors due orientation errors in the Wollaston prism

Except to say that the substrate errors are lower than the coated errors there is not much of a trend in the data given in Table 1.

It can be concluded that for a 0.5° orientation error in the Wollaston prism, average errors in the phase measurement can be as large as 0.5° for the samples examined. The peak to valley of these errors as a function of angle of incidence can be larger than 1° . The Wollaston prism is the only element that causes errors in the measurement of the phase

change on reflection. Proper orientation of this element is essential to good phase measurements. More importantly, it should be noted that improper orientation of the Wollaston prism causes sample dependent errors. The error is not linear or a constant offset. This error cannot be calibrated out via the measurement of a known standard.

Table 2 summarizes the results for the errors in the ratio of reflectance measurement.

<u>1 Degree Orientation Error</u>			
	Substrate	51nm SiO ₂	126nm SiO ₂
Average Error	-8.30%	-6.00%	-6.60%
P/V Error	5.63%	3.03%	4.30%

<u>0.5 Degree Orientation Error</u>			
	Substrate	51nm SiO ₂	126nm SiO ₂
Average Error	-4.15%	-3.00%	-3.30%
P/V Error	2.82%	1.51%	2.15%

Table 2 Summary of the results for the ratio of reflectance errors due to a 1° orientation error in the Wollaston prism

In Table 2 it is evident that the substrate is affected more than the two films. An orientation error of 0.5° in the Wollaston prism causes between 3 and 4 times the average error on the ratio of reflectance measurement as a similar error in polarizers 1 or 2. Correct orientation of the Wollaston prism, therefore, is absolutely essential to measure Ψ .

DISCUSSION OF ERRORS CAUSED BY POLARIZING COMPONENT ORIENTATION ERRORS

Angular orientations of the polarizing components cause errors in the characterization of the ellipsometric parameters.

Polarizers 1 and 2 cause errors in the characterization of Ψ but have no effect on the measurement of Δ . A half-degree orientation uncertainty causes an uncertainty of $\pm 1.7\%$ in the ratio of reflectances. This is a pure scale change in the ratio of reflectances, and could be calibrated out via the measurement of a standard. Importantly, it is sample independent, and can be calibrated out via the measurement of a known sample.

The Wollaston prism orientation affects both phase and modulation. The errors in phase for a 0.5° orientation error cause up to 0.5° of average phase error with a peak to valley of greater than 1° . The errors are sample dependent and therefore cannot be calibrated out. The effect on the measurement of the ratio of reflectance on the angular orientation of the Wollaston prism is three to four times more sensitive than polarizers 1 or 2 and once again, the errors are sample dependent, not a simple scale factor change. An orientation error of 0.5° causes a 4% error in the ratio of reflectance for some samples. To conclude, errors caused by the Wollaston prism are sample dependent and cannot be removed from measurements via calibration.

In order to achieve measurements with an accuracy of 0.1° the orientation of the polarizing components would have to be calibrated to better than 0.05° . The mounts in

the current system do not provide this level of accuracy in the angular orientation. The accuracy of the current mounts is between 0.25° and 0.5° .

POLARIZER EXTINCTION RATIO EFFECTS

The polarizers in the system are made from Polaroid HN42-HE. Information from the vendor indicated that the worst case transmission along the fast axis is 82% while the extinguished axis should have a transmission of less than 0.01%. This is equivalent to an extinction ratio of 1.2×10^{-4} . Modeling indicates that for the samples measured this imperfection causes a nearly constant offset in the phase measurement of 1.25° while having a negligible effect on the modulation measurement. This average error is indistinguishable from the offset caused by the phase change on reflection from the beam splitter coating. The peak to valley variation around this phase error was less than 0.05° . The modulation was changed by less than 0.03%. The peak to valley error due to the extinction ratio of the polarizers is far smaller than the other contributions to the error analysis.

BEAM SPLITTER EFFECTS

Polarization-independent beam splitters, although advertised as such are not truly polarization-independent. There is always some difference in the reflection and transmission between the S and P components. In addition, there are polarization-

dependent phase changes for both the reflected and transmitted beams. This is due to the thin-film nature of the device and the epoxy holding the prisms together.

The derivation of the instrument neglected the polarization-dependent reflection and transmission effects of the beam splitter. When included, these effects cause constant offsets in Δ and a scalar offset on the ratio of reflectance measurements.

The beam from the polarization test arm of the interferometer has been reflected and transmitted from the beam splitter. Therefore, it has both the reflected and transmitted phase change on reflection from the beam splitter encoded into its polarization state. The polarization reference beam, on the other hand, is only transmitted from the beam splitter after transmission through polarizer 2.

When the two beams are recombined, the polarization test arm has experienced both the phase change on transmission and reflection from the beam splitter, but the polarization reference arm has only experienced the phase change on transmission. As a result, there is a constant phase difference between the two beams that is equal to the difference in phase change on reflection from the beam splitter between the P and S polarizations. In other words, the offset between the measured and ideal Δ will be offset by the Δ for reflection from the beam splitter. It is important to note that this is a constant offset and it is sample independent and can be calibrated out via the measurement of a calibration

standard. Another method of measuring this offset would be to remove the sample and measure the system Ψ and Δ . This provides a method of absolute calibration.

In addition to phase change effects in the beam splitter, there are also polarization-dependent amplitude reflections and transmissions in the beam splitter. Beam splitters are never perfect and always have some difference between the amplitude of the reflected or transmitted polarization components. The polarization test beam is reflected and transmitted, while the polarization reference beam is only transmitted by the beam splitter following transmission through polarizer 1. Via derivations in Mathematica, as well as manual derivations, it was determined that this affect does not change the Δ measurement but does cause a scale change in the ratio of reflectance. The scale change is given by Equation (91):

$$\frac{Perturbed}{Ideal} = \frac{|\rho_{Pr}|^2 |\rho_{Pt}|}{|\rho_{Sr}|^2 |\rho_{St}|}, \quad (91)$$

where ρ_{Sr} , ρ_{St} , ρ_{Pr} , and ρ_{Pt} , refer to the S and P amplitude coefficients for the reflected and transmitted waves. In the case that there is no absorption in the coating, ($\rho_{Pr} + \rho_{Pt} = 1$ and $\rho_{Sr} + \rho_{St} = 1$ so that $\rho_{Pr} = \rho_{St}$ and $\rho_{Sr} = \rho_{Pt}$) Equation 20 is given by:

$$\frac{Perturbed}{Ideal} = \frac{|\rho_{Pr}|}{|\rho_{Sr}|} = \frac{|\rho_{St}|}{|\rho_{Pt}|}. \quad (92)$$

For a beam splitter with 52% and 48% reflectivity's this equates to a scale error of 8.3%. Fits to the measured data indicate these reflectances. This error is sample independent, and can be quantified and removed from further analysis. The effect on modulation for the beam splitter has the same effect as the errors caused by improper orientation of polarizer 1 or 2, that is to say it causes a constant scale error. The effects of improper orientation of the two polarizers and the polarization-dependent reflection from the beam splitter are indistinguishable from one another.

To summarize, the beam splitter causes a constant offset in the measurement of Δ and a scalar offset in Ψ . These effects are sample independent and can be calibrated via the measurement of a standard or by removing the sample and measuring the system polarization characteristics.

PHASE-SHIFTING INTERFEROMETRY TECHNIQUES

Phase-shifting interferometry is the data acquisition technique used in the PSIIE. (Creath 1986, Creath 1988) Equation (93) represents the detected interference pattern between two beams A and B with phase difference α and a phase-shifting interferometry phase Φ_{PSI} :

$$I = I_A + I_B + 2E_A E_B \cos(\alpha + \Phi_{PSI}) . \quad (93)$$

In order to extract the phase difference between the beams, three or more frames of data must be acquired with different values of Φ_{PSI} . Phase data taken with the PSIIE uses the

Hariharan algorithm. The Hariharan algorithm (Hariharan 1987) uses five frames of data taken at Φ_{PSI} values in 90° increments. The phase difference between the two beams α , is given by the following equation:

$$\Phi(x, y) = \text{ArcTan} \frac{2\{I_2(x, y) - I_4(x, y)\}}{I_3(x, y) - I_5(x, y) - I_1(x, y)} . \quad (94)$$

As mentioned previously in the section on interferometric ellipsometry, the fringe visibility V is given by the following equation:

$$V(x, y) = \frac{2\sqrt{(I_4(x, y) - I_2(x, y))^2 + (I_1(x, y) - I_3(x, y))^2}}{I_1(x, y) + I_2(x, y) + I_3(x, y) + I_4(x, y)} = \frac{AC\{V\}}{DC\{V\}} . \quad (95)$$

The AC of the modulation in the numerator is the term of interest. It should be noted that the technique of phase stepping is used rather than phase ramping. The PZT is shifted to a given phase increment and then the intensity frame is acquired before the PZT is shifted again for acquisition of the next frame of data. A bucket technique acquires intensity information while the PZT is shifting. This shift during frame acquisition does not affect the measured phase but does cause a reduction in measured fringe modulation that is not desirable in this case.

Given a phase algorithm of the following form:

$$\text{Tan}\{\Phi\} = \frac{N}{D} , \quad (96)$$

where N and D represent the numerator and denominator of a phase algorithm. It can be shown that the fringe modulation using this same set of frames can be given by:

$$V = \frac{\sqrt{(N)^2 + (D)^2}}{I_{Avg}} = \frac{AC\{V\}}{DC\{V\}} , \quad (97)$$

where I_{Avg} is the average intensity of the interferogram. Therefore, the AC component of the visibility can be directly derived from any phase algorithm as :

$$AC\{V\} = \sqrt{(N)^2 + (D)^2} . \quad (98)$$

PHASE-SHIFTING INTERFEROMETRY ERROR ANALYSIS

Imperfections in the movement of the PZT cause errors in the characterization of the phase and modulation. If the PZT does not step in perfect 90° increments, errors in the measurements occur. These phase shifter errors can be broken down into two types of errors, linear and non-linear.

Linear errors are errors in the calibration of the 90° steps. In other words, the steps are not actually 90° but are off by a uniform amount. If a constant calibration error is present, the phase shift may be written as:

$$\alpha' = \alpha(1 + \varepsilon) , \quad (99)$$

where α is the desired phase shift α' is the actual phase shift and ε is the normalized error. The errors due to phase step miscalibration are decreased as the number of steps in

the phase or modulation calculation is increased. For a consistent phase shift error, such as a miscalibration of the phase shifter, a periodic error with twice the spatial frequency of the fringe pattern is seen in the calculated phase. In conventional interferometry, taking measurements with a null fringe will reduce the errors caused by this because the error in the measurement is a function of the phase of the interferogram. If there is a null fringe, then the phase of the interferogram is nearly constant and correspondingly the errors are nearly constant.

In the PSIIE it is not possible to take a measurement with a single null fringe since regions with different Δ 's will by definition have a different phase. In addition, the phase of the S and P interferograms are different, thereby yielding different errors for the two interferograms. As a result, measurements made with null fringes have more errors than those made with fringes.

Nonlinear phase shift errors are also possible, and are more difficult to detect. They often cause greater errors in the extraction of the measured phase or modulation. A nonlinear phase shift error can be written as:

$$\alpha' = \alpha(1 + \epsilon\alpha). \quad (100)$$

A nonlinear phase shift can be partially compensated by the phase shifter calibration so that the total shift over four frames is still 2π . In this case the phase shift becomes:

$$\alpha' = \alpha(1 + \epsilon\alpha - \epsilon). \quad (101)$$

Many authors have developed algorithms to reduce the influence of phase shifter miscalibration and nonlinearity (Creath 1986, Creath 1988, Hariharan 1987, Schmidt and Creath 1995). The techniques involve the use of more frames of data in conjunction with intelligent algorithms to reduce the effects of improper phase shifter calibration and vibration in the measurement of wavefront phase.

The extended averaging techniques developed by Schmidt and Creath (1995) are used to evaluate the improvements possible through the use of more frames of data in the phase-shifting interferometric imaging ellipsometer. The averaging technique was first developed by Schweider et al (1993) and was extended by Schmidt and Creath. The technique begins by taking a generic three or four frame algorithm and extending it to more frames.

The technique begins with a generic algorithm composed of M frames:

$$\tan\{\Phi_M\} = \frac{N}{D}. \quad (102)$$

To calculate a new algorithm for M+1 frames, an N and M can be calculated for the first M frames and then another set of N and M can be calculated for the second to the M+1 frame. A new algorithm can be derived for M+1 frames and is given by Equation (103):

$$\tan\{\Phi_{M+1}\} = \frac{N_1 + N_2}{D_1 + D_2} = \frac{N'}{D'}. \quad (103)$$

This technique can be extended to M+2 frames as shown in Equation (104):

$$\tan\{\Phi_{M+2}\} = \frac{N' + N''}{D' + D''} = \frac{N_1 + 2N_2 + N_3}{D_1 + 2D_2 + D_3} = \frac{N'''}{M'''} \quad (104)$$

This technique can be extended to as many frames as desired. It is a weighted averaging that independently works on the numerator and denominator. It should be noted that a five-frame algorithm based on a 4+1 extended averaging technique yields the Hariharan algorithm.

The technique of extended averaging can be applied to the AC fringe modulation as well. For example, given an AC modulation algorithm:

$$AC_M\{V\} = \sqrt{(N)^2 + (D)^2} = V_M \quad (105)$$

A M+1 frame modulation algorithm would be given by:

$$V_{M+1} = \frac{V_M + V_M'}{2} \quad (106)$$

Since the AC modulation does not have a denominator, the result of applying this technique is a simple averaging and has little benefit.

A more powerful technique uses the derived numerators and denominators from the extended averaging phase calculations (e.g. Equation (104)) and then directly applies Equation (98). For example, from an M+2 frame phase algorithm, a modulation algorithm can be derived as follows:

$$AC\{V\} = \sqrt{(N''')^2 + (D''')^2} \quad (107)$$

where N'' and D'' are given by Equation (104).

In this analysis a goal of 0.1° of error in the measured phase is plotted in the figures. For the modulation characterization an error of 0.1° in Ψ is approximately equivalent to an error in the characterization of the AC modulation of approximately 0.4%. In reality, for a total measurement precision of 0.1° the precision required of the phase-shifting should be much better to leave room for other errors.

Figure 25 illustrates the errors in the characterization of the interferogram phase in the presence of linear and nonlinear phase shifter calibration errors. The plots represent the error in measured phase change on reflection in degrees versus the percentage of phase shifter error. Four algorithms are plotted. The standard four-frame, Hariharan, and a 6 and 7 frame algorithm based on a four-frame technique.

Figure 25 Errors in phase due to linear and non-linear phase shifter calibration errors

It is evident that the errors are reduced as more frames of data are added. In the presence of linear phase shifter errors the generic four-frame algorithm quickly rises off the chart and its performance is unacceptable. The Hariharan is significantly better but a six or seven frame algorithm is far superior. Table 3 illustrates the maximum error for a 5% linear and non-linear calibration error. In the presence of linear calibration errors, an improvement of a factor of 20 or more is realized with the addition of each frame. Nonlinear phase shifter errors cause larger errors. From this analysis, it is evident that a six (4+2) or more frame algorithm is desired to reduce the errors in the phase calculation to levels much less than 0.1° .

Algorithm	Type of Phase Shifter Error	
	Linear	Non Linear
4+0	4.4832	1.1147
Hariharan	0.1769	1.1147
4+2	0.0069	0.0332
4+3	0.0003	0.0328

Errors in Degrees

Table 3 Summary of Peak Phase Errors Due to a 5% Linear and Nonlinear Phase Shifter Calibration Error

Plots of the error in the characterization of the modulation can be found in Figure 26 and a summary of the results can be found in Table 8. Once again, it is clear that the four-frame technique is inadequate and as the number of frames is increased, the errors are reduced. Because of software limitations a four-frame algorithm is being used in the current PSIIE setup. This has limited the precision of the modulation measurements.

Figure 26 Modulation characterization errors due to phase shifter miscalibration

Algorithm	Type of Phase Shifter Error	
	Linear	Non Linear
4+0	7.797%	1.963%
Hariharan	0.305%	1.964%
4+2	0.012%	0.057%
4+3	0.0005%	0.058%

Table 4 Summary of Peak Ratio of Reflectance Errors Due to a 5% Linear and Nonlinear Phase Shifter Calibration Error

The reduction in the errors as the number of frames is increased also approaches a factor of 20 for each frame added. A six frame algorithm appears to be sufficient for reducing the error to well below the specified level of 0.4%.

In conclusion, to reduce the effects of phase shifter errors on the measurement of the phase change on reflection and AC modulation, a minimum of six frames is desired. Software limitations did not allow for the use of this number of frames. If a six frame algorithm were used a factor of 20 improvement in phase and 400 in modulation would be attained.

SAMPLE REFLECTANCE EFFECTS

Sample reflectivity affects the average intensity and fringe modulation in the two interferograms. This has two effects on the measurements. Firstly, the sample reflectance affects the average intensity in the interferogram, and secondly it affects the fringe modulation. Both effect the signal to noise of measurements.

For example, samples cannot be measured near their respective Brewster angle nor at any angle of incidence where either polarization has a low reflectance. At the Brewster angle, the reflectance of the P polarization and therefore its fringe modulation is zero. Phase-shifting interferometry breaks down at this point.

The PSIIE operates via phase-shifting interferometry where, for measurement repeatability, the ideal fringe modulation is one. This maximizes the signal to noise in the measurement. Therefore, if the modulation decreases for the same average intensity, the signal to noise of the measurement has decreased. In order to make measurements via

phase-shifting interferometry, appreciable fringe modulation is desired. The fringe modulation in the PSIIE is determined by Equation (87). If samples have equal S and P reflectances and a Δ of zero, the fringe modulation is 0.5. This is the highest modulation possible. The signal to noise in measurements of samples with low fringe modulation can be poor thereby affecting measurement noise. The samples evaluated all had modulations above 30%.

The PSIIE as presented and constructed has a maximum fringe modulation of 0.5. This occurs because the polarizer in the reference arm reduces the intensity level in that arm by one half. Insertion of a neutral density filter in the test arm of the interferometer doubles the modulation by equalizing the intensities in the two arms of the interferometer. The neutral density filter should be optically flat, AR coated and reduce the intensity in half. In addition, its transmission should be polarization-independent and it cannot have any retardance. Insertion of this neutral density filter would double the fringe modulation.

In order to reduce camera and electronic noise, it is desirable to operate an interferometer just below the saturation level of the camera. Reduction in the average intensity level on a CCD will decrease the signal to noise of a phase-shifting interferometry measurement. Sample reflectance affects the average intensity in the two interferograms. Lower reflectances will cause lower average intensities and lower signal to noise.

The coated regions have lower reflectance than the silicon substrate. The measurements are made with both in the field of view and the intensity level of the source is determined by the region with the highest intensity. The intensity in the substrate region is set to just below saturation and correspondingly the intensity in the coated region is below the saturation level. When examining samples with large variations in surface reflection, the intensity level of the measurement is determined by the region with the highest reflectance. As a result, the signal to noise in the regions with lower reflectances is reduced and the measurement noise in these regions is expected to increase.

Figure 27 illustrates the average intensity in the S and P interferograms for a silicon substrate and a 126nm silicon dioxide film. The intensity is normalized to an arbitrary source intensity but this normalization is identical for both plots. Therefore, the plots are indicative of the intensity levels that are present when a silicon substrate and a 126nm film are measured simultaneously.

A few things are clearly evident. The intensity levels in the two component interferograms and from sample to sample are different. The fact that the two polarizations intensity levels are different, indicates that even when measuring a uniform sample, both interferograms will not have ideal intensity levels. For a silicon substrate measured from 45° to 70° the ratio of intensities in the two polarizations varies from around 1.5 to 3.5. The P component intensity is lower than the S component intensity with worsening effects as the angle of incidence increases. The signal to noise in the P

polarization is lower than the S polarization. When measuring a sample with coated and bare regions, the situation is even worse. The intensity levels of the coated region are 2-5 times less intense than the S polarization for a bare substrate.

Figure 27 Average intensity (arbitrarily normalized) in the S (Solid) and P (dashed) interferograms versus angle of incidence for silicon substrate (left plot) and 126nm SiO₂ film (right plot).

Figure 28 illustrates the fringe modulation for a silicon substrate and a 126nm silicon dioxide film. For the silicon substrate the P modulation does dip significantly as the angle approaches the pseudo-Brewster angle ($\sim 75^\circ$). The 126nm coated sample maintains fairly high modulations over the entire range, but the intensity levels are much lower when measured at the same time as a silicon substrate.

Figure 28 Fringe modulation in the S (Solid) and P (dashed) interferograms versus angle of incidence for silicon substrate (left plot) and 126nm SiO₂ film (right plot).

The AC component of the modulation (also normalized) is plotted in Figure 29. The AC component directly scales with the average intensity in the interferogram. In Figure 27, the effect of the lower average intensity levels due to surface reflectance is evident. When measuring a silicon substrate and a 126nm silicon dioxide film simultaneously, the AC modulation in the film is 2-5 times less intense. Therefore the signal to noise in the coated region is lower.

Figure 29 AC Component of the fringe modulation (arbitrarily normalized) in the S (Solid) and P (dashed) interferograms versus angle of incidence for silicon substrate (left plot) and 126nm SiO₂ film (right plot).

In conclusion, an increase in random errors is expected for the coated regions when measured in the same frame as a silicon substrate.

MEASUREMENT REPEATABILITY

This section will examine the repeatability of measurements. A repeatability of 0.15° and 0.25° for the measurement of Δ has been attained with the use of fringes in the field of

view for a silicon substrate and 126nm SiO₂ film respectively. The repeatability for Ψ is 0.4° and 0.6° for the measurement of a substrate and 126nm SiO₂ film respectively. The errors in measurement to measurement repeatability stem from the precision of the phase shifter and the stability of the optical table. Phase-shifting interferometry is susceptible to these errors (Creath 1986, 1988 Schmidt and Creath 1995).

The Burliegh PZT being used has been shown to perform with accuracies in the angstrom level in systems delivered by the WYKO Corporation (private communication). Two different PZTs were put into the system and performance did not change. Vibration in the optical table is clearly evident by viewing the fringes on a video screen. Although the vibration is reduced at night, it is still evident. Vibration is the largest error source when comparing measurement to measurement repeatability.

In the PSIIE, it is not possible to take a measurement with a single null fringe because regions with different Δ values will have different phases. In addition, the phase of the S and P interferograms are different, yielding different errors for the two interferograms. By averaging over a few fringes, measurements made with fringes in the frame of view can get improved performance over nulled measurements.

The error in phase-shifting is sample dependent because samples have different phase values for the S and P interferograms. When the S and P phase maps are subtracted, the errors due to these effects will be sample dependent.

To demonstrate this, a series of 12 nulled measurements were taken after the instrument had been aligned. As the measurements were being taken the fringes were drifting slowly. As a result, the absolute phase of the interferogram changed from measurement to measurement. If vibration or phase shifter errors are present, the resultant plot of the variation in the measurement should be a sinusoidal function. Figure 30 illustrates the error in the measurements and the sinusoidal function that resulted. The fact that the substrate and thin-films have different errors confirms the hypothesis of sample dependent errors.

Figure 30 Plot of the error in waves of a Δ measurement made with drift between the measurements. The solid line is a silicon substrate and the dotted is a 671nm SiO₂ film on the same substrate measured at 45° angle of incidence.

In order to demonstrate the improvement possible by adding fringes to the field of view and averaging over a few fringes, a series of measurements were made with and without fringes in the field of view. The measurements averaged the Δ in a 35 x 20 pixel region (0.22mm x 1.71nm) for simultaneous measurements made of a silicon substrate and

126nm SiO₂ film at 65° angle of incidence. Twenty measurements were made with and without fringes during the day and at night. The results of these measurements are tabulated in Table 5 and Table 6.

Repeatability of Delta Measurement

	Daytime Measurement		Nighttime Measurement	
	Fringes	Nullled	Fringes	Nullled
P/V	0.525	4.116	0.845	2.891
Stdev	0.154	1.145	0.246	0.847
Units of Degrees				
P/V	1.46 E-03	1.14 E-02	2.35 E-03	8.03 E-03
Stdev	4.28 E-04	3.18 E-03	6.85 E-04	2.35 E-03
Units of Waves				

Table 5 Results of repeatability measurements for silicon substrate Δ .

Repeatability of Delta Measurement

	Daytime Measurement		Nighttime Measurement	
	Fringes	Nullled	Fringes	Nullled
P/V	0.756	6.611	1.020	2.726
Stdev	0.235	1.987	0.281	0.741
Units of Degrees				
P/V	2.10 E-03	1.84 E-02	2.83 E-03	7.57 E-03
Stdev	6.54 E-04	5.52 E-03	7.82 E-04	2.06 E-03
Units of Waves				

Table 6 Results of repeatability measurements for 126nm SiO₂ coating Δ .

Two conclusions can be made from these measurements. Firstly, measurements made with fringes have greater measurement precision. Secondly, measurements made at night are, in general, superior to measurements made during the day. The peak to valley and standard deviation of the measurements is reduced by a factor of 7 to 8 during the day

and by 2.5 to 3.5 at night when fringes are used. The peak to valley and standard deviation are reduced by a factor of 1.4 to 2.5 at night compared to daytime measurements for the nulled measurements. The peak to valley and standard deviation of the measurements with fringes is within 20% to 30% for the day and night measurements. The important thing to notice is the improvement possible by adding fringes to the frame of view. Performance would improve if more frames of data were used in the phase-shifting algorithm.

When considering the values in waves, the standard deviation of the measurements can be as low as is 4.3×10^{-4} or one part in 2300. This equates to a standard deviation of $2.7 \Rightarrow$ when considering the measurement of interferometric phase. This level of performance is excellent. For the measurement of a $20 \text{ \AA}$ silicon dioxide film on a silicon substrate at an angle of incidence of 65° a standard deviation of 0.15° in Δ corresponds to a thickness variation of $1 \text{ \AA}$.

The repeatability of the measurement of Ψ was evaluated separately and is expressed as a percentage error in the ratio of reflectance measurement. A 1% error is equivalent to a 0.4° error in Ψ .

Repeatability of Ratio of Reflectance Measurement

	Nulled	Fringes
Substrate	1.99%	1.05%
126 nm Coating	2.76%	1.50%

Table 7 Results of repeatability measurements for ratio of reflectance measurement

The repeatability of the phase-shifting interferometric imaging ellipsometer should be compared to the performance of other imaging ellipsometers presented. Using nulling techniques, Liu et al. (1990) reported an accuracy of 5nm, while Mishima and Kao (1981, 1982) reported an accuracy of 10nm. Using multi-frame techniques, Cohn et al (1988) report RMS errors of 0.36° with peak to valley variations of 2.5° . Pak and Law (1995) in the most impressive instrument report 0.057° accuracy.

The PSIIE has achieved a single point repeatability of 0.15° for Δ and 0.4° for Ψ equivalent to a thickness sensitivity of $1\text{\AA}$. This is superior to all the investigators except for Pak and Law (1995). Their measurements were limited to samples measured at their Brewster angle with thicknesses much less than the wavelength of light. As far as measurement repeatability is concerned, the phase-shifting interferometric imaging ellipsometer is a precise instrument comparable to any of the imaging ellipsometers presented. corresponds to a thickness variation of $1\text{\AA}$.

ERROR ANALYSIS SUMMARY

There are a variety of factors that influence the performance of the phase-shifting interferometric imaging ellipsometer. The orientation and quality of the polarizing components, the quality of the phase-shifting interferometry, signal to noise effects and spurious reflections all effect the measurements.

The orientation and quality of the polarizing components cause systematic errors and affect the precision of the instrument. The precision of the system is limited by the quality of the rotation mounts used for the polarizing components. They are inexpensive and are not motorized. The precision of the mounts used for the polarizing components provides for 0.25° - 0.5° precision. This level of component orientation accuracy causes peak to valley phase errors of up to 1° and average errors approaching 0.5° . The error in modulation could be as large as 3-4%. In order to improve these systematic errors due to component alignment, higher quality mounts are needed with accuracies approaching 0.05° . This is consistent with the accuracies required in classical ellipsometers.

Random errors are caused by the quality of the phase-shifting interferometry, spurious fringe effects and signal to noise effects. The software used in the PSIIE uses a five-frame phase algorithm and a four-frame modulation algorithm. In the presence of phase shifter errors on the order of a 5% linear and non-linear phase shifter error, measurement errors between 0.2° and 1° of random error in phase and 2-8% error in the modulation are expected. Similar errors are expected in the presence of vibration.

Each additional frame of data used in a phase-shifting algorithm reduces these errors by a factor of 20. The use of a six-frame algorithm could reduce the errors to below 0.04° and 0.06% for the phase and modulation characterization respectively. This level of precision is required for the PSIIE to be commercially viable.

The data acquisition technique has limitations in the types of samples and angles of incidence that are measurable. If the sample is measured near its pseudo Brewster angle, or has very low P polarization reflection, the P interferogram would have little or no modulation. In this case the phase-shifting interferometry technique does not perform well. Large amounts of measurement noise would be present. The instrument is limited to samples and angles of incidence that have enough reflectance in both polarizations to measure the sample. Samples with large surface reflectance variations cause measurement problems for similar reasons. This limitation exists in many types of imaging ellipsometers because the signal to noise for any acquisition technique would be low when the sample reflectance varies.

Many of the optics in the PSIIE are not coated (lenses and the Wollaston prism) and the ones that are coated are broad band AR coated. The lack of high quality laser coatings and the sheer number of surfaces involved cause spurious fringes to be present in the system. In addition, the polarizers used cause spurious fringes. All of these factors cause noise to be present in the measurement. When data is averaged over a number of pixels this effect can be reduced or eliminated, but the lateral resolution of the instrument is compromised as a result. In order to reduce the spurious fringe effects high quality laser coatings on all surfaces are required.

In conclusion, the limiting factor for high accuracy measurements is the orientation of the polarizing components. The precision of the measurements is limited by the phase-shifting algorithm. Noise within a measurement frame is limited by spurious fringes. Better mounts, coatings and phase-shifting software would improve performance. The repeatability of the instrument is 0.15° , achieving a measurement noise of less than $1\text{\AA}$. The accuracy of the instrument varies from 0.7° to 1° for Δ and 0.93% to 2.19% for Ψ .

RESULTS OF EXPERIMENTATION

To illustrate the imaging ability of the PSIIE, a pair of two dimensional ellipsograms are presented. The two dimensional illustrations show the measurement of delta and the ratio of reflectances for a 126nm SiO_2 film on a silicon substrate at an angle of incidence of 65° . The rectangular region is the coated region and is surrounded by the silicon substrate.

The plots are displayed as OPD plots using software provided by the Wyko Corporation. For the measurement of Δ , this phase data needs to be converted into degrees by multiplying by 360° and dividing by the wavelength. The ratio of reflectance plot does not need to be scaled.

Figure 31 illustrates the measured Δ for a fictitious wavelength of 1000 . Therefore, 500nm represents 180° , a half of a wave. In the PSIIE, this represents a Δ of 0° . This

180° offset occurs because of the sign conventions used in ellipsometry. X and Y traces through the center of the measured data are also displayed. The origin of the two-dimensional display is in the lower left corner.

The substrate has a delta of -4° and the beam splitter imparts a 14° offset resulting in a phase measurement of 538nm ($500\text{nm} + ((-4^\circ + 14^\circ)/360^\circ) * 1000\text{nm}$) in Figure 31. The coated region has a delta of -70° corresponding to 350nm in Figure 31. Noise and spurious fringe effects are evident.

Figure 31 Measurement of Delta

Figure 32 illustrates the two dimensional ratio of reflectance measurement. The coated region has a ratio of reflectance of approximately 3 while the substrate has a value of 0.3. Increased noise in the coated region is evident.

Figure 32 Measurement of the ratio of reflectance

The PSIIE was used to measure two silicon dioxide coated silicon wafers from VLSI Technologies. The samples were measured at angles of incidence from 45° to 70° in 1° increments. Three different types of samples were measured, two silicon substrates, a 51nm and a 126nm SiO₂ coating on silicon. The measurements were made on 2/2/99-2-3/99 following a calibration of the instrument. In each measurement, the coated and uncoated regions were examined simultaneously via the imaging nature of the instrument.

Plots illustrating the measurements will be presented followed by a discussion of the results. Each figure consists of two plots. A plot illustrating the measured data and the modeled theoretical data versus angle of incidence is presented, followed by a plot of the error in the measurement. The units of the Δ plots are degrees while the plots of $\tan \Psi$ are unitless. The plot of the errors in the measurement of Δ is the difference between the

measured and theoretical. The plot of the errors in the measurement of $\tan \Psi$, on the other hand, is the ratio of the measured to theoretical.

The theoretical data was calculated in Mathematica using the characteristic matrix approach for thin-film analysis (Macleod 1989). The film thickness and index of refraction were chosen for the best fit to the measured data. Because it is known that imperfections in the orientations of the polarizers and Wollaston prism are anticipated because of mount limitations, the orientation of these components was allowed to vary in a $\pm 0.5^\circ$ range to accomplish a good fit to the measured data.

The Ψ data is plotted as the ratio of reflectances of the P to S polarizations and is unitless. In classical ellipsometry the rotation angle of a polarizer or compensator is the unit of measure. This is usually a direct measurement of the angle Ψ and as a consequence classical ellipsometric analysis usually considers the angle Ψ . In this presentation, the tangent of Ψ will be considered because the PSIIE actually measures the ratio of reflectances as shown in Equation (88) not the angle Ψ . The errors in the ratio of reflectance are plotted as the ratio of the measured to theoretical data.

SILICON SUBSTRATE MEASUREMENTS

Figure 33 through Figure 36 illustrate the results of the measurements of the two silicon substrates. The Δ and ratio of reflectances are plotted for each sample as well as the error in the measurement as a function of the angle of incidence.

Figure 33 Δ measurement in degrees and the error in degrees versus angle of incidence for silicon substrate 1.

Figure 34 Ratio of reflectance measurement and error expressed as a ratio of measured to modeled versus angle of incidence for silicon substrate 1.

Figure 35 Δ measurement in degrees and the error in degrees versus angle of incidence for silicon substrate 2.

Figure 36 Ratio of reflectance measurement and error expressed as a ratio of measured to modeled versus angle of incidence for silicon substrate 2.

SiO₂ COATED SILICON MEASUREMENTS

Figure 37 and Figure 38 illustrate the results for the measurement of the 51nm thin-film of SiO₂ while Figure 39 and Figure 40 show the results for the 126nm thin-film of SiO₂.

Figure 37 Δ measurement in degrees and the error in degrees versus angle of incidence for 51nm silicon dioxide thin-film on silicon substrate 1.

Figure 38 Ratio of reflectance measurement and error expressed as a ratio of measured to modeled versus angle of incidence for 51nm silicon dioxide thin-film on silicon substrate 1.

Figure 39 Δ measurement in degrees and the error in degrees versus angle of incidence for 126nm silicon dioxide thin-film on silicon substrate 2.

Figure 40 Ratio of reflectance measurement and error expressed as a ratio of measured to modeled versus angle of incidence for 51nm silicon dioxide thin-film on silicon substrate 2.

DISCUSSION OF RESULTS

The functional form of all of the measurements agrees with the theoretical data. This verifies that the phase-shifting interferometric imaging ellipsometer measures the ellipsometric parameters as illustrated by previous derivations. The fact that substrate and coated regions are measured in the same frame of data proves that the instrument operates as an imaging ellipsometer.

Table 8 details the errors in the measurement of the ellipsometric parameter Δ . The average error, peak to valley (P/V), root mean squared (RMS) and the standard deviation of the errors are listed for all four samples. The average error is the average difference between the theoretical and measured data as a function of the angle of incidence. This can be considered an offset between the measured and theoretical data. The phase change on reflection from the beam splitter causes all of the data to be offset from the

theoretical data by approximately 14° . This has already been removed from the data. The average error in the four measurements varies from -0.117° to 1.859° . The peak to valley of the errors in each measurement is fairly constant at 3.3° . The RMS error varies from 0.7° to 0.98° while the standard deviation of the errors varies from 0.71° to 1° .

	Substrate 1	Substrate 2	51nm SiO ₂	126nm SiO ₂
Average Error	1.515	1.859	0.079	-0.117
P/V Error	3.327	3.222	3.360	3.370
RMS Error	0.757	0.696	0.841	0.983
Standard Deviation of Error	0.772	0.710	0.857	1.003

All quantities in Degrees

Table 8 Summary of Errors in Δ Measurement

The peak to valley, RMS and standard deviation of the errors in the Δ measurement remain fairly constant and indicate that the errors in the system are systematic, and tend not to vary over time or with the sample. The measurements were made one day apart, and the noise appears to have remained constant over that one day timeframe. The variation from sample to sample is approximately 30% with increased values for the coated samples.

Table 9 details the errors found in the ratio of reflectance measurements. The errors in the ratio of reflectances are represented as the ratio of the measured data to the modeled data and the ideal value would be one. The average error shown in Table 9 has the one subtracted. The errors represent a percentage error in the measurement.

The average error represents an offset in the measurement. The average error varies from -0.16% to 1.9% . The statistical errors (P/V, RMS and standard deviation) for the substrate measurements were lower than the corresponding errors for the coated samples. This agrees with the findings of the phase change on reflectance measurements.

	Substrate 1	Substrate 2	51nm SiO ₂	126nm SiO ₂
Average Error	1.91%	1.93%	0.65%	-0.16%
P/V Error	4.69%	4.35%	5.90%	9.37%
RMS Error	0.91%	0.82%	1.56%	2.14%
Standard Deviation of Error	0.93%	0.84%	1.59%	2.19%

Table 9 Summary of Errors in Ratio of Reflectance Measurement

In conclusion, the measurements made with the PSIIE indicate that the instrument correctly measures the ellipsometric parameters according to theoretical derivations and calculations. When measuring at multiple angles of incidence, the RMS error in Δ is $0.7-1^\circ$ and the RMS error in Ψ is 0.9% to 2% .

CONCLUSION

Theoretical derivations and measurements indicate that the phase-shifting interferometric imaging ellipsometer measures the ellipsometric parameters Ψ and Δ . The PSIIE has many unique characteristics that to the author's knowledge have not been examined elsewhere. The PSIIE utilizes the techniques of polarization interferometry and is the first imaging ellipsometer to use phase-shifting interferometry as its data acquisition technique.

The PSIIE has many advantages over a conventional ellipsometer. First, the ellipsometric parameters are acquired over a two dimensional area in a single measurement using a solid state PZT. The removal of all actively rotating components is a great simplification in the mechanical design of the system. Secondly, unlike a classical ellipsometer, the PSIIE contains no compensator, expanding the range of wavelengths that can be measured. Hence, the instrument can be operated over a range of wavelengths with the addition of a tunable laser source.

The data acquisition technique, phase-shifting interferometry, has proven to be an extremely accurate and repeatable measurement technique. Phase-shifting has the repeatability to achieve a measurement precision of 0.1° . In the current embodiment, software restrictions limited the precision. Four frames are used in the characterization of the ratio of reflectance and a five frame algorithm is use to measure Δ . The addition of

more frames would increase measurement precision by a factor of 20 for each additional frame in the algorithm. Using six frame algorithms would reduce the phase-shifting errors for the Δ and ratio of reflectance characterization by a factor of 20 and 400 respectively.

The effect of spurious fringes is the most significant point to point noise source in the PSIIE. Since the design uses a coherent laser source, reflections from the faces of the beam splitter, polarizers and Wollaston prism add coherently producing a small but calculable error in the measured phase and modulation of the interferograms.

The largest contributor to systematic errors in the system is the alignment of the polarizing components. Peak to valley errors of up to 1° are caused by an improper orientation of 0.5° . The mounts in the system limit the absolute accuracy of the system to this level.

Because the PSIIE is an interferometric instrument, vibration isolation is required. This is a costly requirement and limits the portability of the instrument. Poor vibration isolation increases measurement errors.

The PSIIE has limitations in the types of samples and angles of incidence that are measurable. Samples must not be measured near their pseudo Brewster angle and there must be enough reflection in both polarizations for adequate fringe modulation. In

addition, the variation in reflectance across a measurement region must be small for the same reasons.

The theory of the first interferometric imaging ellipsometer and the measurement results from a prototype instrument have been presented. Repeatability of the instrument is between 0.15° and 0.5° with absolute accuracies below 1° . Improvements in phase-shifting interferometry, hardware and the optical coatings would allow the instrument to reach its full potential. These improvements would reduce the repeatability to 0.1° or better. This is the repeatability commonly quoted for single point commercial ellipsometers. Improved mounting hardware and calibration techniques would significantly improve the absolute accuracy.

FUTURE WORK

The prototype of a novel ellipsometer has been presented. Improvements in hardware and software are needed to maximize system performance.

Improved optical coatings are needed for all surfaces in the PSIIE to reduce the deleterious effects of spurious fringes. In the current embodiment, many surfaces are uncoated and the ones that are coated have broad band AR coatings. Improved coatings would reduce the surface reflections by at a factor of 10-100. Improved rotation mounts

with a precision of 0.05° should be used for all polarizing components to permit more accurate and repeatable alignment of their orientation.

The placement of a neutral density filter in the test arm of the interferometer would increase the fringe modulation of the interferograms by a factor of 2, improving the signal to noise ratio. A digital camera with a minimum of 10-bit resolution should be employed to further improve the signal to noise ratio in the system. Software modifications are required to utilize more steps in the phase-shifting. A minimum of six frames should be employed.

These improvements will allow the calibration techniques presented to reach their full potential. Analysis indicates that this should reduce the systematic errors due to the orientation of the polarizing components to 0.1° . Following the implementation of these improvements, other calibration and measurement techniques may need to be employed to further improve performance. One potential technique is the insertion of a quarter-wave plate between the sample and the interferometer. This will improve the fringe modulation of some samples. Measurements of a sample with and without a wave plate in the beam may help to average out systematic errors.

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