A phase shifting interferometeric imaging ellipsometer

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Abstract

An imaging ellipsometer has been developed which employs phase shifting interferometry to characterize the ellipsometeric parameters. Polarized light from a laser or incoherent source is collimated and reflected off of the surface under test. A modified Michelson interferometer is used in conjunction with a Wollaston prism to generate two interferograms with orthogonal polarization states. Subtraction of the phases in the two interferograms yields the ellipsometeric parameter Δ. The fringe modulation[8] of the two interferograms is used to calculate the ellipsometeric parameter Ψ. The instrument uses imaging optics to image the surface under test to a CCD, yielding a truly two dimensional ellipsometeric measurement. The design of the instrument and results of measurements will be presented.

Keywords: Ellipsometry, Interferometeric Ellipsometry, Thin Films, Phase Shifting Interferometry, Interferometry, Imaging Ellipsometer

1. Introduction

Many authors have designed and tested interferometric ellipsometers[1-2]. In addition, imaging ellipsometers[3-4] based on conventional ellipsometeric techniques have been developed. The impetus of this work is the development of an imaging ellipsometer employing phase shifting interferometry to characterize the ellipsometeric parameters. A number of novel layouts were identified, but the layout in figure 1 was chosen for the building of a prototype.

2. Theory and Instrument Layout

Figure 1 illustrates the layout of the instrument. A light source is collimated and directed through a polarizer oriented at 45 degrees. This source can be a laser or an incoherent source such as an LED. The light is then reflected off the sample of interest before passing into a modified Michelson interferometer. The Jones matrix for the light hitting the sample and entering the interferometer are

$$E_{source} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad \text{Eq. 1}$$

$$E_{Interferometer\ Input} = \begin{bmatrix} \rho_s \\ \rho_p \end{bmatrix} \quad \text{Eq.2}$$

Where $\rho_s = |\rho_s| e^{i\Phi_s}$ and $\rho_p = |\rho_p| e^{i\Phi_p}$ are the complex amplitude reflection coefficients for the object of interest. All subsequent references to reflectance will refer to the complex amplitude reflection. Since this ellipsometer is imaging a two dimensional region, the phases are a function of position.

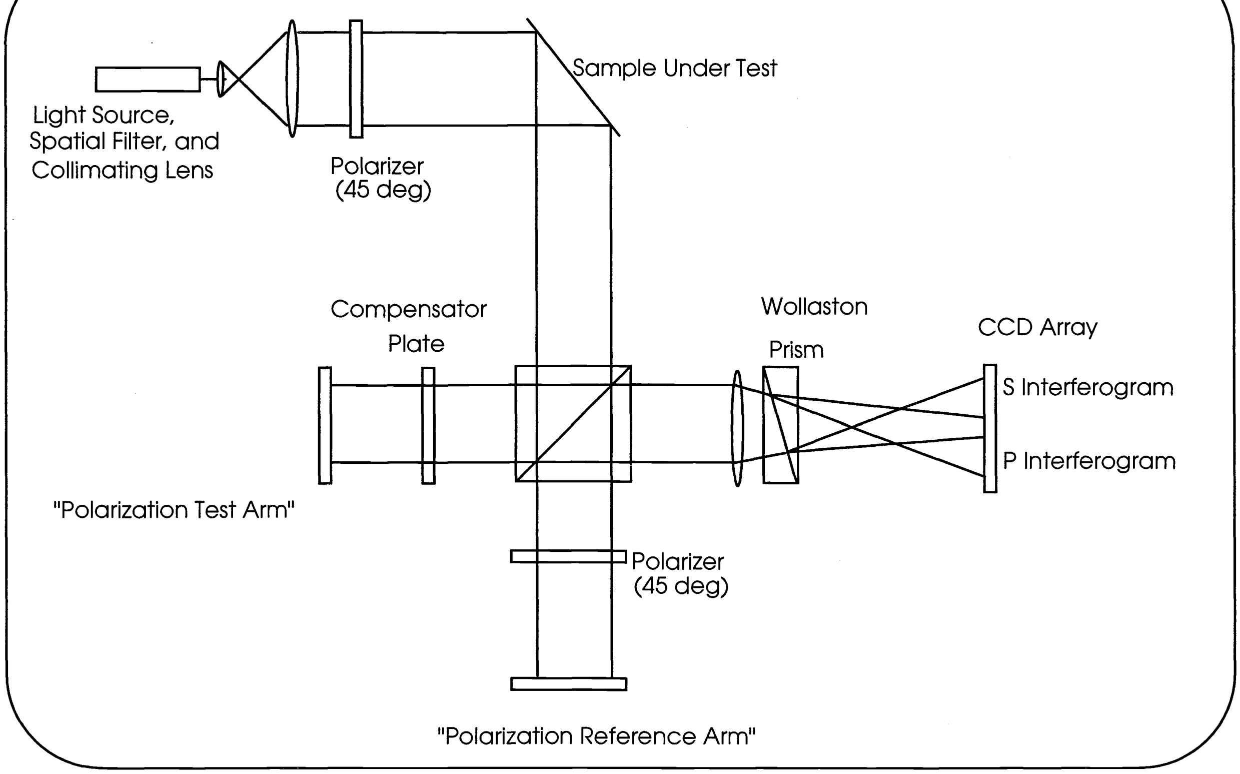


Figure 1. Layout of Instrument

The ellipsometeric parameter Δ is defined as the difference between the P and S phase change on reflection. The ellipsometeric parameter Ψ is defined as the inverse tangent of the ratio of the P and S reflectances.

$$\Delta = P\ Phase - S\ Phase = \Phi_p - \Phi_s \qquad \text{Eq. 3}$$

$$Tan\{\Psi\} = \frac{\rho_p}{\rho_s} \qquad \text{Eq. 4}$$

The light is directed into the interferometer by a non-polarizing beam splitting cube. This cube is path matched to ensure high contrast fringes when using an incoherent source.

One arm of the interferometer has a polarizer oriented at 45 degrees. This arm can be thought of as a "polarization reference arm" as far as the polarization phase measurement is concerned. This polarizer "scrambles" the polarization phase of the incoming beam by generating a linearly polarized beam from an arbitrarily polarized beam. By definition, a linearly polarized beam has identical phases for the S and P polarizations.

The polarization state of this linearly polarized beam will be compared to the other arm of the interferometer. The electric field returning to the beam splitter from the "polarization reference arm" is

$$E_{reference\ Arm} = \frac{1}{2}\frac{1}{\sqrt{2}}\begin{bmatrix}\rho_s+\rho_p\\ \rho_p+\rho_s\end{bmatrix}e^{i\Phi_{RA}} = \frac{1}{2}C_0\begin{bmatrix}1\\1\end{bmatrix}e^{i\Phi_{RA}} \qquad \text{Eq. 5}$$

Where $C_0 = \frac{1}{\sqrt{2}}(\rho_s + \rho_p) = |C_0| e^{i\Phi_{C_0}}$. The term Φ_{RA} represents any polarization independent phase errors due to component imperfection within the reference arm of the interferometer. The ½ and $\sqrt{2}$ come from the amplitude transmittance of the 50/50 beam splitter and the polarizer respectively.

The other arm consists of a compensator plate and return mirror. The compensator is required for incoherent illumination. This arm preserves the phase change on reflection information in the S and P polarization states and can be thought of as the "polarization test arm" for the polarization phase measurement being made. This arm also contains a piezo-electric transducer (PZT) for performing phase shifting interferometry (PSI). Φ_{PSI} represents the phase induced from movement of the PZT while the Φ_{TA} represents the phase errors due to component imperfection in the test arm. The Jones matrix for the beam returning to the beam splitter from the "polarization reference arm" is therefore

$$E_{Test\ Arm} = \frac{1}{2}\begin{bmatrix} \rho_s \\ \rho_p \end{bmatrix} * e^{i(\Phi_{PSI} + \Phi_{TA})} \quad \text{Eq. 6}$$

The beams are recombined and directed through an imaging lens and a Wollaston prism oriented at 0 degrees. The lens images the surface under test onto the CCD camera, while the prism serves to split the S and P polarizations into two distinct interference patterns on the CCD camera. The electric field coming into the Wollaston prism and the resulting interference patterns are:

$$E_{Wollaston\ Prism} = E_{reference\ Arm} + E_{test\ Arm} = \frac{1}{2} C_0 \begin{bmatrix} 1 \\ 1 \end{bmatrix} * e^{i\Phi_{RA}} + \frac{1}{2}\begin{bmatrix} \rho_s \\ \rho_p \end{bmatrix} * e^{i\Phi_{PSI} + \Phi_{TA}} \quad \text{Eq. 7}$$

$$I_s = |E_s|^2 = \left| \frac{C_0}{2} e^{i\Phi_{RA}} + \frac{\rho_s}{2} * e^{i(\Phi_{PSI} + \Phi_{TA})} \right|^2$$
$$I_p = |E_p|^2 = \left| \frac{C_0}{2} e^{i\Phi_{RA}} + \frac{\rho_p}{2} * e^{i(\Phi_{PSI} + \Phi_{TA})} \right|^2 \quad \text{Eq 8-11}$$
$$I_s = |E_s|^2 = \frac{1}{4}\{C_0^2 + \rho_s^2 + 2\ |C_o|\ |\rho_s|\ Cos\{\Phi_s + \Phi_{PSI} + \Phi_{RA} + \Phi_{TA} + \Phi_{C_0}\}\}$$
$$I_p = |E_p|^2 = \frac{1}{4}\{C_0^2 + \rho_p^2 + 2\ |C_o|\ |\rho_p|\ Cos\{\Phi_p + \Phi_{PSI} + \Phi_{RA} + \Phi_{TA} + \Phi_{C_0}\}\}$$

Phase shifting interferometry[5-7] is used to measure the phase of each interferogram. Phase algorithms involving 3 or more phase steps can be used and are discussed in the above references. The measured phases for the two interferograms are

$$Measured\ S\ Phase = \{\Phi_s + \Phi_{RA} + \Phi_{TA} + \Phi_{C_0}\}$$
$$Measured\ P\ Phase = \{\Phi_p + \Phi_{RA} + \Phi_{TA} + \Phi_{C_0}\} \quad \text{Eq.12-13}$$

Two phenomenon are present in the interference patterns. One is the measurement of component imperfections and polarization phase is the other.

Component imperfections are assumed to be polarization independent and therefore will be the same for the S and P beam. In this way the S and P interferograms are considered to be common path once co-registered and subtracted pixel by pixel. The sum $\Phi_{RA} + \Phi_{TA}$ represents the component imperfections in the interferometer and is common to both interferograms. The phase offset in the reference arm, Φ_{C_o}, is also common to both interferograms.

The only terms that are not common to both interferograms are the S and P phase change on reflection terms. In order to measure the ellipsometeric parameter Δ , the measured P phase is subtracted from the measured S phase.

$$\Delta \ = P\ Phase - S\ Phase \ = \ \Phi_p - \Phi_s . \quad \text{Eq.14}$$

The parameter Ψ can be determined via the visibility of the fringes in the two interferograms. The fringe visibility is defined as γ =(Imax-Imin)/(Imax+Imin). This is identical to the ratio of the AC to DC components of the interference pattern. The visibility of the P and S interferograms can be expressed as:

$$\gamma_p = \frac{\frac{1}{4}\rho_p C_o}{\frac{1}{4}\rho_p{}^2 + \frac{1}{8}C_o{}^2} \qquad \text{Eq.15-16}$$

$$\gamma_s = \frac{\frac{1}{4}\rho_s C_o}{\frac{1}{4}\rho_s{}^2 + \frac{1}{8}C_o{}^2}$$

The ratio of the AC components of the visibility yields the ratio of reflectances.

$$Tan\{\Psi\} \ = \frac{\rho_p}{\rho_s} \quad \text{Eq. 17}$$

Therefore, through the phase and visibility of the two interferograms, this instrument measures the two ellipsometeric parameters.

Two effects have been ignored for clarity. These are the phase change on reflection from the beam splitter coating and the polarization dependant reflections from the beam splitter coating. These are polarization dependent and will therefore affect the Δ and Ψ calculations. Terms representing this effect could be included above and are assumed to be uniform across the aperture. The resulting offsets in Ψ and Δ will be the same for all samples and angles of incidence and their effect can be measured by removing the sample and directing a linearly polarized beam directly into the interferometer. Therefore, the offsets can be measured and removed from subsequent measurements as part of a calibration procedure.

3. Measurements

Measurements of SiO_2 thin films on Si substrates have been made at a range of angles of incidence. Charts 1 and 2 illustrate the measurement of a 51.3nm coating using LED illumination at 644 nm. Charts 3 and 4 illustrate the measurement of a 943nm coating using a HeNe laser. The measurements were made on calibration samples from VLSI Technology of the transition region between the coated and uncoated regions of a silicon wafer. Each chart illustrates the results for the coated and substrate region for a single measurement at multiple angle of incidences.

Figure 2 Delta Characterization for 51.3 nm SiO2 Coating on Si

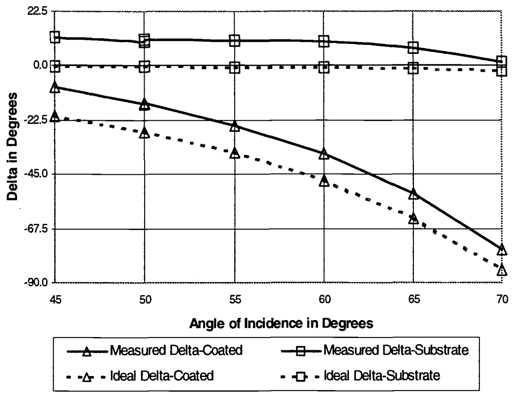


Figure 3. Ratio of Reflectences for 51.3 nm SiO2 Coating on Si

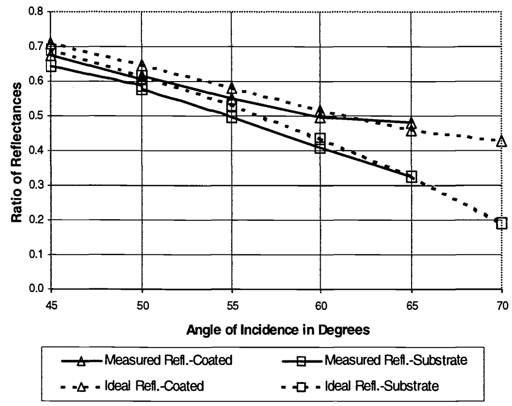


Figure 4. Delta Characterization for 943 nm SiO2 Coating on Si

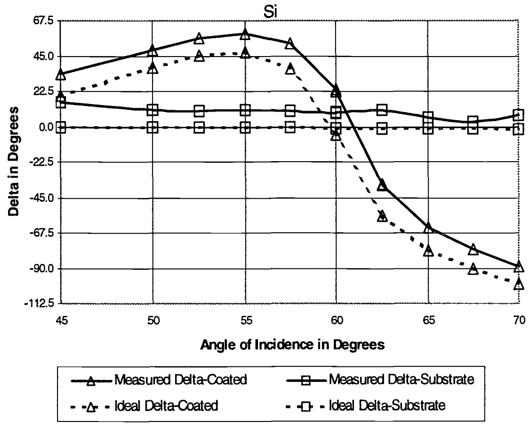
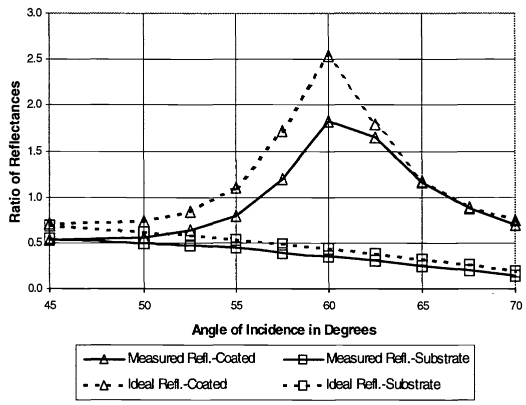


Figure 5. Ratio of Reflectences for 943 nm SiO2 Coating on Si



The functional form of the phase change on reflection data agrees well with the theoretical predictions. An offset between the measured and ideal Δ of around 10 degrees can be seen in the plots. This can be attributed to the phase change on reflection from the beam splitter coating and has been confirmed by removing the sample and directing the light directly into the interferometer.

Since the instrument measures the ratio of reflectances directly, ratio of reflectance data ($\tan(\Psi)$) is plotted rather than Ψ. In this way, constant offsets in the data remain as an offset, whereas if the arc-tangent were used, an offset would no longer be constant. The 51.3 nm ratio of reflectance data functional form is quite good with an average offset to the theoretical data of 0.025. The agreement for the 943 nm coating is not as good. The substrate data has an average offset of 0.088 while the coated data suffers from larger errors that vary with the angle of incidence. At the time of printing, work is under way to determine the source of these errors.

4. Conclusion

The theory of a new imaging phase shifting ellipsometer has been presented. Results from a prototype instrument indicate good agreement to theory. Future work will concentrate on the reduction of systematic errors and calibration techniques.

References

1) Hazebroek H F and Holscher A A 1973 "Interferometeric ellipsometry" *J. Phys. E: Sci. Instrum.* **6** 822-826

2) Lin C, Chou C and Chang K, 1990 "Real time interferometric ellipsometry with optical heterodyne and phase lock in techniques" Applied Optics V 29 #34 pp5159-5162
3) Cohn R. F., Wagner J W, Kruger J 1988 "Dynamic imaging microellipsometry: theory, system design, and feasibility demonstration" Applied Optics V 27(22) pp4664-4671 November 15, 1988
4) Mishima T, Kao K C 1982 "Detection of thickness uniformity of film layers in semiconductor devices by spatially resolved ellipsometry" Optical Engineering Col 21(6) pp1074-1078 Nov/Dec 1982
5) Creath, K "Phase measurement interferomety techniques" in Progress in Optics XXVI. E. Wolf editor Elsevier Science Publishers 1988
6) Schmit, J, Creath K, 1995 "Extended averaging technique for derivation of error-compensating algorithms in phase shifting interferomety" Applied Optics Vol 34(19) pp3610-3619
7) J. E. Grievenkamp and J H Brunning, "Phase Shifting Interferometry" Ch 14 in Optical Shop Testing, Second Edition, Ed D. Malacara 1992 John Wiley and Sons
8) Wells, C 1997 "Fringe modulation characterization for a phase shifting imaging ellipsometer" SPIE Proceeding vol 3134-51