

The Effect of Phase Change on Reflection on Optical Measurements

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Abstract

Phase change on reflection affects many precision dimensional measurements. The phase change can result in erroneous height measurements. The phase change on reflection was investigated at a glass-metal interface using samples with evaporated metal strips on the back surface of a wedged glass substrate. The samples were measured on a phase shifting interferometer and the phase change was calculated from the apparent measured step heights from the internal reflection at the back glass-metal interface. The background subtraction process was the largest contributor to the phase change uncertainty. The measured phase change for gold, copper, and aluminum is $131.4^\circ \pm 3.8^\circ$, $173.73^\circ \pm 3.8^\circ$, and $200.7 \pm 3.8^\circ$, respectively.

1.0 Introduction and Background

Many precision dimensional measurements are based on interferometry which inherently relies on the reflection of light from a target. Upon reflection, light undergoes a phase change. This phase change on reflection depends on the material properties and can introduce a bias in the measurement. The phase change on reflection varies with incident angle, material properties, wavelength, and material depth. This variation affects measurements ranging from precision radius of curvature (by changing the cat's eye position), center thickness, gage block calibration, to scanning white light interferometry (SWLI) [1]. The goal of this research is to measure the phase change on reflection as a function of incident angle, material, and material depth as well as to determine its resultant effect on measurements such as the radius of curvature.

The phase change on reflection depends on the index of refraction of the material on both sides of the interface. The index is complex for metals and in some precision applications the small imaginary component of nominally transparent materials cannot be ignored. Refractive index values are published for many materials [2-4], however these values are often contradictory, presumably due to variations in material composition and/or film thickness. Furthermore, the optical properties of many alloys are not well known. Thin films, like those used in MEMS devices (which are commonly measured with SWLI), often do not have the same material properties as the bulk material. Interferometry is well suited to measure phase changes, but a difference measurement must be made where the phase change is compared between two materials. A typical configuration is to deposit a region of material A on a substrate of material B and then measure the apparent step height of material A. However, the physical step height must be known to determine phase change on reflection differences [5]. The physical step height contribution can be intrinsically removed by depositing

regions of the metal on the back side of a glass substrate and measuring the phase profile of light reflected internally from the back surface. Such investigations have been carried out with SWLI [6], but the angle of incidence and wavelength dependence cannot be easily investigated with this method. In an early experiment [7], fringes of equal chromatic order were used to investigate the phase change on reflection over a range of wavelengths. In this experiment, the phase was not directly measured, but calculated through fringe counting.

We have investigated the phase change on reflection by using a combination of methods discussed in the literature. We are using phase shifting interferometry (PSI) and a sample geometry where an internal reflection is exploited to intrinsically remove the step height from the measurement. Our initial studies focus on normal incidence reflection for a range of metals with 632.8 nm wavelength light. Future work will investigate film thickness, angle of incidence, and wavelength dependence. In this work, we describe the theory behind the measurement, the experimental configuration, and present examples of experimental results.

2.0 Theoretical Calculations

The phase change was measured when light reflects from a non-absorbing media (glass) and an absorbing media (metal) interface, as indicated in Figure 1. The glass has an index of refraction of n_1 , and the metal has a complex index of refraction, $n_2 - ik_2$. We first consider the case of normal incident light, $\theta_1=0^\circ$ where, the state of polarization is inconsequential. The phase change for both the s- and p-polarization states are equal [8]. For normal incidence, the Fresnel amplitude reflection coefficient, r is given by

$$r = \frac{n_1 - n_2 + ik_2}{n_1 + n_2 - ik_2} \quad \text{Eqn. 1 [8].}$$

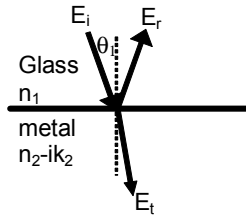


Figure 1: An electric field, E_i , from glass is incident from a glass substrate on bulk metal at an angle of θ_1 . The electric field is reflected (E_r) and transmitted in part (E_t).

The angle between the incident field, E_i , and the reflected field, E_r , is the absolute phase change on reflection, ϕ . The tangent of the phase change is the ratio of the imaginary component of r to the real component,

$$\tan \phi = \frac{2n_1 k_2}{n_1^2 - n_2^2 - k_2^2} \quad \text{Eqn. 2 [8].}$$

While the phase change on reflection is a function of the thickness of the metal, we first consider the case of a bulk material. Published values of n and k [2-4] vary, even within the same source. Using the complex index of refraction for copper, gold, and aluminum from Palik [2] and Eqn. 2, the phase change on reflection was calculated, as shown in Table 1. The values of n and k were interpolated for the He-Ne wavelength which introduced an uncertainty due the choice of fit parameters, as indicated in the ϕ column. The glass substrate used was fused silica with has an index of refraction of 1.457 [9]. The Range column in Table 1 also shows the range of calculated phase change values using various published values [2-4].

Table 1: The complex index of refraction and the calculated phase change values at $\theta_1=0^\circ$, for glass to metal using reference Palik [2].

	n	k	ϕ°	Range, ϕ_s°
Cu	0.41	3.40	134.1 ± 0.0	1.1
Au	0.15	3.25	131.7 ± 3.2	0.8
Al	1.40	7.60	159.0 ± 1.9	3.2

3.0 Experimental Plan: Sample Preparation

The samples were 12.7 mm diameter glass substrates with 3.0 mm wide strips of evaporated metal as shown in Figure 2. The metal was deposited using a Varian 3125 Vacuum Thin Film System. The metal strips have a nominal height of 500 nm. The height was determined by a quartz crystal thickness monitor in the evaporator and confirmed using a calibrated profilometer. The original mask used in the evaporator is shown in Figure 3.

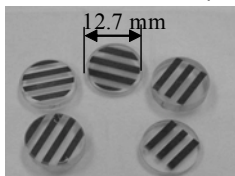


Figure 2: The samples with Au, Al, or Cu.

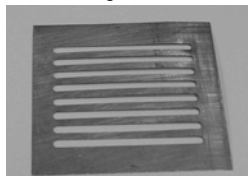


Figure 3: The 50 mm square metal mask.

A redesigned mask and fixture was manufactured (see Figure 4) to reduce shadowing effects and to allow one mask to be scanned during evaporation. This will allow us to create metal films with a ramp profile for future studies.

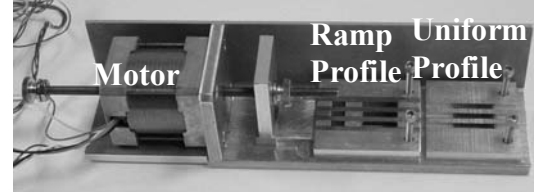


Figure 4: The redesigned fixture: motor, the location for the ramp profile, and the location for the uniform profile.

3.1 Experimental Plan: Measurements

A Veeco/Wyco PSI was used to measure the phase change. The sample was configured for a back measurement as shown in Figure 5. By measuring through the sample, we are directly measuring the phase change difference between a glass-air interface compared to a glass-metal interface. A front configuration would measure the phase change plus the step height. A Claphamdue flat was used as the transmission flat. This provides a reasonable fringe contrast between the glass and metal regions of the sample and greatly improves measurement quality. A picture of the measurement is shown in Figure 6.

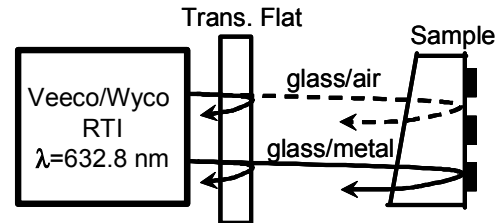


Figure 5: The measurement configuration for normal incidence. The substrate is wedged to prevent interference from the front surface.

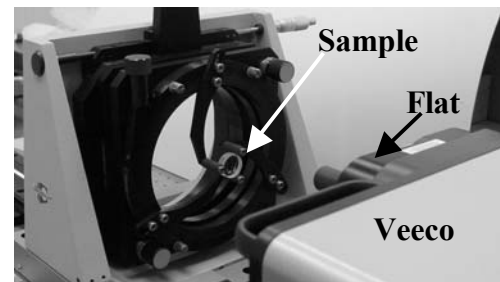


Figure 6: The sample as measured in the interferometer.

The apparent step height observed in the data is the phase change at the glass/metal interface relative to a glass/air interface. The absorption of fused silica is very low, consequently the phase change on reflection is

approximately zero (for an internal reflection). This assumption leads to a negligibly small contribution to the final uncertainty.

4.0 Analysis and Results

Because the measurements were conducted through the glass substrate, the inhomogeneities and surface figure error of the glass are included in the phase change measurement. To correct for this, the back of the substrate was measured in the same configuration and nominally the same position before the metal was deposited. This background measurement was then subtracted from all subsequent measurements. This was done for each substrate. The subtraction process leads to a significant contribution to the uncertainty and is discussed in more detail below.

An example measurement after background subtraction is shown in Figure 7. It is essential to note that the apparent height shown in Figure 7 is not a physical height, but an artifact of the phase change on reflection. All of the light is reflected from the nominally flat back of the glass substrate. The apparent height, h , is converted to phase, ϕ , using in the wavelength of the laser, 632.8 nm, and

$$\phi = \frac{4\pi h}{\lambda} \quad \text{Eqn. 3}$$

The additional factor of 2 in Eqn. 3 is because the phase change measurement is double pass for height features but single pass for phase change measurements.

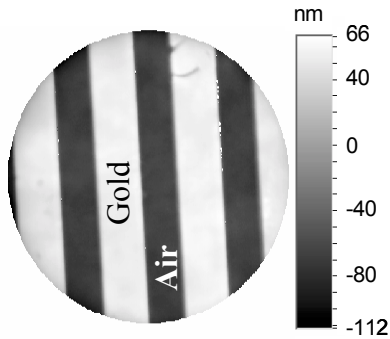


Figure 7: A measurement post background subtraction.

We used the multiple region analysis tool in the Vision software to separate the metal and air regions and to calculate the *RMS*, the number of points, and the mean value of each region. The difference between the mean value for the air and metal regions is the phase change on reflection for the glass/metal interface. The number of points and *RMS* are used to calculate the uncertainty in the mean value.

4.1 Uncertainty

We have investigated the primary sources of uncertainty and estimated their contribution to the measured phase change using a gold measurement as an

example for all of the following cases. Variations in the evaporation process create a level of uncertainty not studied here, but will be investigated in the future.

The RMS of each area (metal and air), when divided by the square root of the number of points indicates the uncertainty in the mean value (phase). Without subtraction, the uncertainty in the phase of the metal and air regions are both 0.09°, with subtraction, they are 0.07° and 0.06°, respectively. This reduction demonstrates importance of the background subtraction.

A major source of uncertainty is the background subtraction. The pre- and post-deposition samples can not be repositioned exactly in the same orientation in the interferometer. Rotation, translation, and zoom differences occur between the two measurements. The trimming of the edge pixels also contributes to uncertainty. Shadowing effects require that the edge of each strip be trimmed. This trimming is subjective.

A simplified Monte Carlo simulation was performed to determine the uncertainty associated with repositioning and trimming. In software, we manipulated the data, performed the normal subtraction process, and calculated the resultant phase change. The manipulation was done such that it would be comparable to our best effort at repositioning in the lab: translating ± 20 pixels in both x and y, rotating $\pm 10^\circ$, zooming $\pm 5\%$, and trimming 0 to 5 pixels. The phase change for each of the above manipulations was calculated. The worst case for each situation is shown in Table 2. The difference from the non-manipulated case is indicated in the Difference column. These differences were then combined in a root sum square method to calculate the uncertainty associated with repositioning and trimming, 3.8°.

Table 2: Calculated phase change for the worst case for each case for an example measurement of gold.

Without Subtraction	140.5°	
With Subtraction	132.1°	
With Subtraction and Manipulation		Difference
Trim	133.8°	1.7°
Rotate	132.5°	0.4°
Zoom	135.5°	3.3°
Translate	132.2°	0.1°
Subtraction Uncertainty:		3.8°

Repeatability and reproducibility studies helped to determine the environmental effects of our measurement. Reproducibility was measured by removing the sample from the interferometer, waiting a day, and repeating the measurement. The repeatability of the measurement is 0.26° and reproducibly 0.50°. The final uncertainty is then

calculated by combining all the above uncertainties in a root sum square method. The final combined uncertainty for phase change is on reflection for this experimental method is 3.8° .

4.2 Measured Phase Change

The gold sample was measured on three days, twenty times each, for a total of 60 measurements, where each measurement was an average of eight. The calculated average phase change for gold was $131.4^\circ \pm 3.8^\circ$, corresponding to a height change of $115 \text{ nm} \pm 3.8 \text{ nm}$. This compares well to numbers shown in Table 1 from the literature.

The results for the copper and aluminum samples are only preliminary because we were unable to take measurements of the substrate before the metal was deposited. A modified background subtraction was done, though. In software, the metal region of the measurement was masked out. A Zernike analysis was performed on the remaining glass region. Using these Zernike coefficients, a simulated substrate was generated, which was used for subtracting the blank substrate.

The aluminum and copper samples were measured 20 times each, where each measurement was an average of eight. The calculated phase change for copper is $173.73^\circ \pm 3.8^\circ$, and aluminum $200.7^\circ \pm 3.8^\circ$. These numbers do not agree well with the values from Table 1. For comparison, the phase change for gold using the same method is 137° . Future measurements will determine if this variation is due to the modified subtraction process or another variable.

5.0 Continuing Work

Thus far, we have studied the phase change on reflection for different metals. In the future, we will investigate the dependence of the phase change on film thickness and incident angle, and compare measurements at 632.8 nm and 1550 nm .

The capability now exists to manufacture samples with varying film thickness by moving the mask relative to the substrate during the evaporation process. The metal strips will range in thickness from zero to several times the skin depth [3]. The measurement procedure will be the same. However, the analysis will result in a line plot of phase change versus film thickness instead of one number for phase change. This will be compared to theoretical calculations [3].

By using PSI and a skip flat geometry [10] we will directly measure phase change on reflection as a function of angle of incidence. With this geometry we will investigate the angle dependence from 0° to approximately 25° . These results are necessary to determine the effect of phase

change on reflection on the radius of curvature measurement.

6.0 Conclusions

The measured phase change for gold, copper, and aluminum is $131.4^\circ \pm 3.8^\circ$, $173.73^\circ \pm 3.8^\circ$, and $200.7^\circ \pm 3.8^\circ$, respectively. By far, the largest contributor to the uncertainty of the phase change is the subtraction process. In the subtraction process, the zoom factor had the greatest effect. Future work could reduce this uncertainty by repositioning the sample to better than $\pm 5\%$ zoom.

Acknowledgments

The authors would like to thank Research Corporation, the National Institute of Standards and Technology, the Center for Precision Metrology, and the National Science Foundation (grants #EEC9811556 and #EEC0331950) for their support of this work. Any opinions, findings, conclusions and/or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the above named institutions. The authors would also like to thank John Hudak at UNC Charlotte for his assistance with the evaporator.

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