Determining the Optical Properties of a Thin Film

Abid Jeem and Jeb North
Washington and Lee University
Physics and Engineering Department

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In this paper, we investigate the optical properties and thickness of a thin film of silica nanoparticles upon a silicon wafer. Results were obtained using a filmetric thickness measurement system. The ability to accurately categorize the physical and optical properties of thin films is a process crucial for increasing the transparency of optical coatings and in material sciences.

I. INTRODUCTION

Thin film interference is a phenomenon governed by the fundamental principles of wave reflection and superposition. Using information regarding a material's index of refraction, numerous conclusions can be drawn about a sample's characteristics. This investigation is oriented towards the application of thin-film interference to determine, firstly, the thickness of a given sample of silica nanoparticles and, secondly, its optical properties. To gain information regarding these characteristics, we will utilize spectroscopic reflectometry, a technique that relies on measuring the reflection of light from a sample's surface, and the reflectance spectrum obtained from the filmetric apparatus using the apparatus' broadband light sources and high-precision spectrometers. The ability to accurately identify a thin films characteristic is a crucial factor in ensuring the performance and reliability of thin films in their applications within semiconductor devices, optical coatings, and biomedical sensors.

A. Thin Film Interference

Superposition is the wave phenomenon in which the existence of two or more waveforms at the same point in space appear as a single wave produced by the combination/superposition of their waveforms. Superposition is also the principle that drives thin film interference. When light waves encounter a film a component of the light's waveform transmits through the film and another portion reflects from the film's surface. When the component of light transmitted through the surface of the film encounters the second surface of the film, it is split again, sending a wave signal back through the first surface of the film parallel to the waveform initially reflected, visualized in image [1]. Any observation of the reflected light now yields the superposition of these two waveforms. Following the initially transmitted wave's interaction within the film, its frequency returns to the frequency of the initial light. The appearance of the two waves' superposition is then left to the phase difference between the two waves. As the initially transmitted wave moves through the film, its phase relative to the initially reflected ray changes. It is the index of refraction, which determines the speed of the light within the film, and the thickness of the film that dictate how long the initially transmitted light is within the film, and thus its phase change.

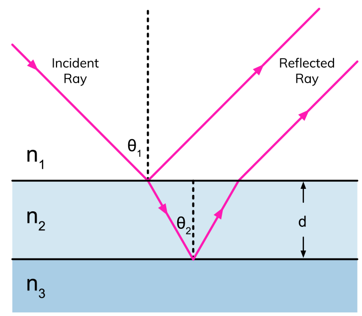

FIG. 1. Illustration of thin film interference for a film of arbitrary index of refraction (n_2) and a ray of arbitrary incident angle (θ_1). Figure from ref[1].

Knowing the distance traveled by the initially transmitted light to be $2d$, for an orthogonal incident angle ($\theta_1 = 0$) as in our experiment, the wavelength of the light within the medium to be $\lambda_{film} = \frac{\lambda_{air}}{n_{film}}$, and that any phase shift by an integer of λ_{air} will cause the peaks of each signal to align, yielding positive interference, the expected wavelengths of positive interference, given by reference [2] become:

$$\lambda_{construcive} = \frac{2nt}{m} \tag{1}$$

Where lambda is the light's wavelength in air, taken to have an index of refraction $n_{air} = 1$, t is the thickness of the film, n is the film's index of refraction, and m is a positive integer. Considering the same principles, the expected wavelengths for destructive interference are given by reference [2] to be:

$$\lambda_{destructive} = \frac{4nt}{2m+1} \tag{2}$$

It is the wavelengths of positive and constructive interference or any other trends observed in the reflection or transmission spectrum that categorize the optical properties of a film. Note that both of the equations above can be rearranged to give expressions for the thickness of a film t, allowing for the extraction of a sample's thickness if the index of refraction and wavelengths of positive/negative interference are known.

II. EXPERIMENTAL OVERVIEW

In both our investigation of the silica nanoparticle thin film thickness and its optical properties we will be utilizing a filmetric apparatus. While the silicon wafer that the thin film lies upon allows no transmission of light, the filmetric apparatus is capable of observing both reflection and transmission spectra, allowing it to fully categorize the behaviors of various mediums. Following a brief calibrating procedure using a silicon wafer with no nanoparticle thin film, the filmetric device must be aimed to a region of the wafer covered by nanoparticles before it can take the broad band spectrum it will use to determine the thickness of the film. It is the visual analysis of this broad band spectrum that allows investigators to categorize the optical properties of the film.

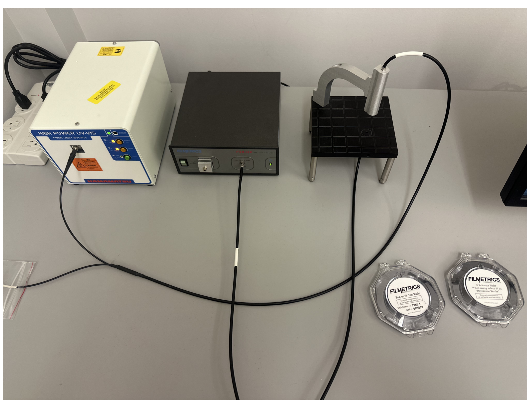

FIG. 2. Experimental setup used for measuring thin film thickness using the Filmetrics reflectometer system featuring a broadband light generator (left), signal processor (middle), and sample platform (right)

III. RESULTS AND ANALYSIS

The measured reflectance spectrum of the SiO_2 on Si reference wafer was analyzed using the built-in Filmetrics software. By fitting the experimental reflectance curve to a theoretical model of a single-layer SiO_2 film on a silicon substrate, the software estimated the film thickness to be:

$$(724.5 \pm 7.2)\,\mathbf{nm}$$

The reported uncertainty of ± 7.2 nm corresponds to the Filmetrics system's typical specification of $\pm 1\%$ for thin film thickness measurements in this range [3].

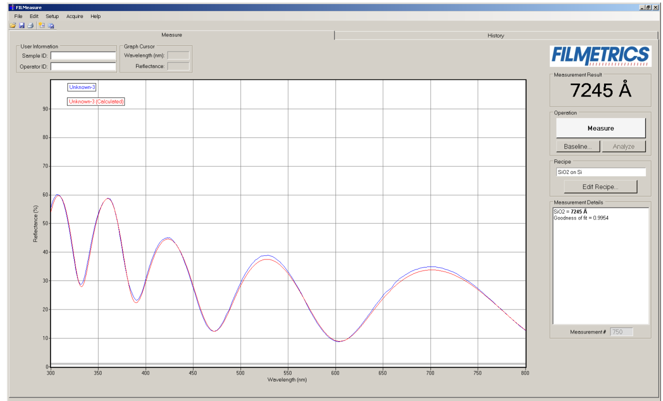

FIG. 3. Reflectance spectrum and fitted model for the SiO_2 on Si reference sample. The Filmetrics software estimated a film thickness of 7245 Å, which closely matches the manufacturer-provided value of 7240.1 Å. The accuracy of the fit (0.9954) confirms the reliability of the measurement.

The manufacturer's label on the test wafer stated a nominal thickness of **7240.1 Å**, as shown in Figure 4. The measured value differs by only **4.9 Å**, which falls well within the expected uncertainty bounds and supports the accuracy of the apparatus's measurement.

FIG. 4. Photograph of the reference wafers used in the experiment. The left container shows the SiO_2 on Si test wafer with a labeled thickness of 7240.1 Å and serial number 09K023. The right container holds the Si reference wafer used during system calibration.

To further validate the software's result, the reflectance spectrum was exported as a CSV file and compared against a custom theoretical model coded in Python. The model used the Fresnel equation for reflectance at normal incidence, equation 3, to determine the theoretical coefficients of reflection at each interface of the thin film, $SiO_2 - air$ and $SiO_2 - Si$, that were used to determine the intensity of the total reflected signal within the model. The film thickness was fixed at the measured value of 724.5 nm. As shown in Figure 5, the theoretical curve closely matches the amplitude and spacing of interference fringes in the experimental data, confirming that the film thickness is physically consistent with the observed optical behavior.

$$R = \frac{n_1 - n_2}{n_1 + n_2} \quad (3)$$

Given by reference [4], where n_1 represents the refractive index of the medium the wave is traveling within and n_2 represents the refractive index of the reflecting material.

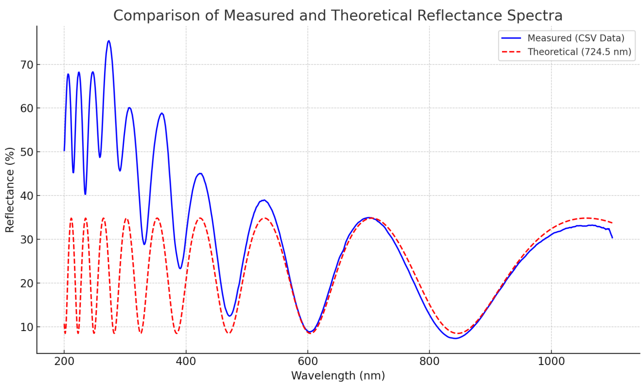

FIG. 5. Comparison of the measured reflectance spectrum (blue) from the experimental CSV data and the theoretical reflectance model (red dashed) for a 724.5 nm thick SiO_2 film on silicon. The alignment of interference fringes confirms the accuracy of the measured film thickness.

The interference fringes observed in the reflectance spectrum arise from multiple internal reflections within the SiO_2 thin film. These reflections interfere constructively and destructively depending on the optical path length, as described in Section IA, which is determined by the film thickness and refractive index.

Using the experimental values for n (given to be 1.46), d, (724.5 nm), and the interference order, m, we can approximate the peak spacing in the spectrum. For example, using $m = 1$, the first-order constructive interference would occur around:

$$\lambda = 2nd = 2(1.46)(724.5) \approx 2115.4 \text{ nm}$$

Since this is outside the visible range, higher-order interference dominates the observed spectrum. The periodic spacing and number of peaks between 300–800 nm are consistent with expectations for a film of this thickness, reinforcing the validity of the result.

In summary, the final result for the thin film thickness was determined to be:

$$d = (724.5 \pm 7.2)\,\textbf{nm}$$

This result is supported both by manufacturer reference data and independent theoretical validation using the experimental spectrum.

IV. ERROR ANALYSIS

The uncertainty in the measured film thickness, reported as (724.5 ± 7.2) nm, is based on the Filmetrics system's specified accuracy of $\pm 1\%$ for thin film measurements in this range [3]. This estimate reflects the precision of the automated fitting routine used by the Filmetrics software, which employs least-squares optimization to match experimental reflectance spectra to simulated models that account for optical dispersion and instrumental noise [5].

Possible sources contributing to this uncertainty include imperfections in the initial calibration using the bare silicon wafer. Any slight misalignment or surface debris on the reference could propagate through all subsequent measurements. While gloves were used during sample handling, contamination from dust or oils could still slightly distort the reflectance spectrum by introducing local scattering. Furthermore, while the Filmetrics fitting engine incorporates wavelength-dependent refractive indices, the simplified theoretical model used for our Python-based validation assumed constant values, which may introduce small discrepancies in predicted fringe locations.

Nonetheless, the high degree of agreement between the measured value and the manufacturer's labeled thickness of 7240.1 nm—a difference of just 4.9 Å, or 0.07%—is well within the estimated uncertainty range. The uncertainty, while acknowledged, does not significantly alter our interpretation of the data or the confidence in the conclusions drawn from it.

V. CONCLUSIONS

This study provides a tutorial for a method of determining the properties of thin films. The application of thin films in precise practices and technology such as semiconductor devices, optical coatings, and biomedical sensors, emphasizes the importance of methods that allow for their convenient and accurate characterization. The filmetric apparatus's ability to provide measurements of thickness and optical spectra in excellent agreement with the values previously attained and expected for the sample is a testament to the effectiveness of interferometry as a method of categorizing thin films. Further investigations utilizing this filmetric apparatus could analyze the optical behaviors of media beyond silica particles.

[1] Harvard Natural Sciences Lecture Demonstrations, Thin film interference (n.d.), accessed: 2025-03-24.

[2] LibreTexts, Interference in thin films (n.d.), accessed: 2025-03-24.

[3] I. Filmetrics, F30 thickness measurement instrument series, https://www.filmetrics.com/thickness-measurement/f30 (2023), accessed April 5, 2025.
[4] Fibercore, Fresnel reflection (n.d.), accessed: 2025-03-30.
[5] I. Filmetrics, *F20 User Manual* (2022), accessed April 5, 2025.