

Research on the measurement technology of film thicknesses based on endoscopic hyperspectral imaging

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Semiconductor oxide thin films are widely applied in the internal cavity mirror protection of lasers and inner wall coatings of semiconductor device due to their excellent optical transparency and thermal stability. Film thickness is critical for functional performance, yet conventional methods cannot obtain *in situ* spatial distribution of film thickness within confined internal structures. To address this limitation, this study proposes a novel *in situ* film thickness measurement method integrating fiber optic endoscope with hyperspectral imaging. First, optical defocusing is first employed to mitigate intensity differences caused by the endoscope's honeycomb pattern. Second, the calibration of pseudo-color images is performed based on the reflectance spectra of the thin film. Finally, considering the endoscope's field of view angle, the incident angle is recalculated, and film thickness is inverted using spectrum fitting method. Experimental results demonstrate that the developed method successfully captures the reflectance spectrum at each spatial point on the film surface, and generates an accurate thickness distribution map. The thickness fitting results, after the incidence angle correction, are highly consistent with ellipsometer measurements, with an average relative error of less than 1%. This work provides a promising solution for large-area thickness inspection of the thin films in confined spaces.

Keywords: film thickness measurement, endoscopic hyperspectral imaging, *in situ* inspection, spectrum fitting.

1. Introduction

In the field of semiconductor oxide thin films, cerium oxide (CeO_2), as an important functional ceramic material [1], has attracted considerable attention in applications such as optical coatings, semiconductor devices [2], and protective layers for laser cavity mirrors [3] owing to its excellent optical transparency, high thermal stability, strong anti-friction properties [2], and unique catalytic and self-cleaning potential [4]. In these

applications, the film thickness [5,6] is a key parameter for optical performance, mechanical strength, and functional reliability. For example, in chemical laser systems, the thickness uniformity of cerium oxide films used to protect cavity mirrors directly influences the damage threshold and resistance to thermally induced deformation [7]. While traditional spectroscopic ellipsometry [8] can provide accurate thickness measurements, they are generally unable to acquire spatial thickness distribution and are unsuitable for the internal structures of these devices. Consequently, the development of an *in situ* thickness measurement technology with high spatial resolution is crucial for process optimization, quality control, and performance assessment.

In recent years, the integration of hyperspectral imaging (HSI) with endoscopic technology has opened a revolutionary path to addressing this challenge. In general, the endoscopic hyperspectral technology has been predominantly explored for medical diagnosis. For instance, ARNOLD *et al.* [9] proposed a hyperspectral endoscope system for surgical tissue classification, which combines fluorescence imaging and white-light reflectance spectroscopy to provide additional spectral diagnostic information during tissue observation. To mitigate substantial image distortion during endoscopic procedures, YOON *et al.* [10] designed a hyperspectral endoscope capable of simultaneously acquiring internally co-registered hyperspectral and standard white-light images, and then computationally compensated for image distortion, allowing the endoscope to reconstruct accurate hyperspectral data cubes while moving within the cavity. THOMASSEN *et al.* [11] compared the performance of a hyperspectral camera equipped with an endoscope and an open hyperspectral system, both systems were used for image acquisition in patients undergoing gastrointestinal resection surgery, and the perfusion measurements provided by the endoscopic hyperspectral camera were found to be as accurate and reliable, as those obtained with the open hyperspectral system. LIU *et al.* [12] constructed a rapid spectral endoscopic imaging system that can reconstruct quantitative distribution images of physiological parameters such as tissue blood volume in mice by constructing a calibration coefficient matrix and an optical model of tissue, without requiring labeled visualization to describe tissue morphological characteristics. BALI *et al.* [13] created an endoscopic hyperspectral imaging system for intraoperative visualization of tumor regions in head and neck cancer surgery. This HSI workflow facilitates *in vivo* tissue identification during surgery, delivering accurate visual results rapidly with minimal disruption to standard surgical procedures. Since hyperspectral imaging combines spectral analysis with spatial imaging, it can provide continuous spectral information for each pixel within a field of view, offering an ideal solution for mapping film thickness distribution. Nevertheless, reports on the combination of hyperspectral and endoscopic technologies for film thickness measurements in confined spaces remain scarce.

This paper presents an *in situ* film thickness measurement method based on a fiber optic endoscopic probe coupled with hyperspectral imaging. To address the intensity inhomogeneity due to the honeycomb structure of the fiber bundle, a defocusing ap-

proach is employed. Pseudo-color images are acquired by a hyperspectral camera based on thin-film reflectance. Moreover, the incident angle is compensated for analytical deviations in thickness caused by the large field of view during spectral imaging. Ultimately, spectrum fitting is employed to achieve the accurate thickness of thin films. This approach allows for large-area thickness mapping in confined spaces and holds significant potential for *in situ*, online monitoring of thin films.

2. Experimental methods

2.1. Endoscopic hyperspectral imaging system

To acquire spectral image information of the target in confined spaces, an endoscopic imaging system based on a hyperspectral camera was established (as shown in Fig. 1). The system comprises three main components: an illumination source, a fiber optic endoscope, and a hyperspectral camera. A clip-on LED was employed as the illumination source, providing uniform irradiation on the sample surface. The fiber optic endoscope (diameter: 2 mm, length: 1000 mm, field of view: 76°, working distance:

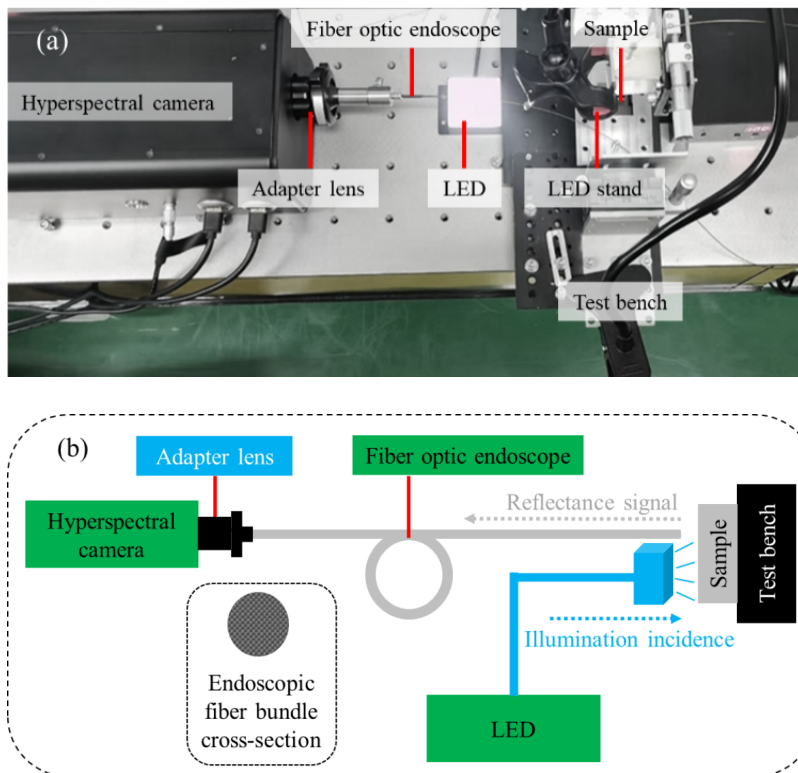


Fig. 1. Endoscopic hyperspectral imaging system. (a) Device prototype. (b) Schematic diagram.

3–10 mm) consists of an optical fiber bundle containing 10,000 individual fibers. Its probe collects the reflected light from the object surface, which is then directed through a bayonet adapter lens into the push-broom hyperspectral camera. The camera is based on a complementary metal oxide semiconductor (CMOS) detector with a pixel size of $5.86 \mu\text{m} \times 5.86 \mu\text{m}$, 480 spatial pixels, and a spectral range covering 400–1000 nm across 300 spectral bands. Three red-green-blue (RGB) bands at 640 nm, 532 nm, and 471 nm were selected for pseudo-color image display.

2.2. Sample preparation and characterization

The sample substrate is a $25 \text{ mm} \times 25 \text{ mm}$ single-sided polished silicon wafer. The film is deposited using a magnetron sputtering vacuum coating machine, and the purity of the cerium oxide target material is greater than 99.99%. Four thicknesses of cerium oxide thin films were prepared using different deposition times.

The spectrometer was used to perform single-point reflectance spectroscopy measurements on the samples. The ellipsometric spectrometer was employed for single-point film thickness measurements on the samples.

2.3. Experimental principle and process

2.3.1. Honeycomb structure artifact suppression

An optical bayonet adapter lens contains a fixed-focus lens. Adjusting the knob to position the lens appropriately reveals the distinctive honeycomb pattern inherent to the fiber optic endoscope [14], which affects the spectral performance. Therefore, by gradually adjusting the knob to change the lens position, the image can be defocused and blurred, thereby eliminating the honeycomb pattern in the endoscope.

2.3.2. Hyperspectral reflectance calculation

To quantify the true reflectance of the sample and eliminate the influence of the imaging light source on the thin film sample, hyperspectral data of the sample, reference, and dark noise are collected separately, from which the reflectance of the sample can be obtained

$$R_{\text{sample}}(\lambda) = \frac{DN_{\text{sample}}(\lambda) - DN_{\text{dark}}(\lambda)}{DN_{\text{reference}}(\lambda) - DN_{\text{dark}}(\lambda)} R_{\text{reference}}(\lambda) \quad (1)$$

where $R_{\text{sample}}(\lambda)$ represents the reflectance of the sample at a given wavelength λ . DN_{sample} , $DN_{\text{reference}}$, and DN_{dark} are the light intensity values in the hyperspectral data collected from the thin film sample, the substrate silicon wafer, and in dark condition, respectively. $R_{\text{reference}}(\lambda)$ is the reflectance of the silicon wafer substrate at a given wavelength λ .

2.3.3. Simulated annealing algorithm overview

Simulated annealing (SA) is a probabilistic optimization algorithm inspired by the annealing process in metallurgy [15]. It is used to find an approximate global optimum for complex optimization problems, particularly for those with numerous local optima.

The algorithm simulates the physical process where a material is heated and then slowly cooled to eliminate defects and achieve a low-energy crystalline state. At each iteration, SA generates a new solution by perturbing the current solution. Unlike greedy algorithms that only accept better solutions, SA allows for the acceptance of worse solutions with a certain probability, enabling it to escape local optima. This acceptance probability is governed by the Metropolis criterion and is influenced by a control parameter analogous to temperature. The probability of accepting a worse solution decreases as the temperature drops during the cooling process. By gradually lowering the temperature, the algorithm initially explores the solution space widely and eventually converges to a (near-)global optimum.

2.3.4. Spectrum fitting

A spectrum fitting program is developed based on the SA algorithm to process the measured reflectance spectra. The program iteratively adjusted key parameters, including film thickness, within predefined feasible ranges. For each parameter combination, a theoretical reflectance spectrum was recalculated using the transfer matrix method [16]. The optimal film thickness across wavelength points was identified when the discrepancy between the calculated and measured reflectance spectra was minimized.

2.3.5. Incidence angle correction

When the fiber optic endoscopic probe is positioned for normal incidence on the thin film sample surface, the incidence angle is typically set to 0° by default during spectrum fitting for film thickness determination. However, due to the inherent field of view (FOV) of the endoscope, the reflected spectra from different spatial points within the FOV correspond to varying incidence angles, leading to deviations in film thickness analysis. Therefore, correction of the incidence angle is necessary. In this context, the incidence angle at the edge of the FOV is denoted as

$$\theta = \frac{1}{2} \text{FOV} \quad (2)$$

where FOV stands for the field of view angle of the fiber optic endoscope.

Given the probe-sample distance, the incidence angle at an arbitrary FOV point is obtained from its radial distance to the FOV center. Using trigonometric formulas, the actual incidence angle corresponding to that point is derived as

$$\theta_{\text{point}} = \arctan\left(\frac{L_{\text{point}}}{L_{\text{surface}}}\right) \quad (3)$$

where L_{point} represents the distance from a certain spatial point to the center point of the field of view, and L_{surface} denotes the distance from the probe to the sample surface.

2.4. Evaluation metrics

2.4.1. Spectral similarity measurement

To quantitatively assess the improvement in reflectance spectra after defocusing, two widely used spectral similarity metrics [17] were employed: the spectral angle mapper (SAM) and the root mean squared error (RMSE).

2.4.2. Image quality evaluation

The quality of the calibrated hyperspectral images was assessed using the peak signal-to-noise ratio (PSNR) and the structural similarity index (SSIM) [18]. SSIM value closer to 1 signifies greater structural similarity to the reference image, denoting a more effective calibration.

2.4.3. Film thickness evaluation

The accuracy of the fitted film thickness was evaluated using the relative error (RE), which expresses the discrepancy between the measured and reference (or true) values as a percentage. The uniformity of the film thickness distribution across the sample surface was characterized by the relative standard deviation (RSD).

3. Results and discussion

3.1. Impact of honeycomb structure on light intensity

To analyze the impact of the fiber bundle's honeycomb structure on hyperspectral imaging, a standard whiteboard was imaged under focused and defocused conditions, as shown in Fig. 2. Owing to optical defocusing, the evident honeycomb-like pattern in Fig. 2(b) is nearly eliminated in Fig. 2(c), resulting in a more uniform imaging area. A comparison of the light intensity profiles on the marked lines across three RGB bands (640, 532, and 471 nm) before and after defocusing reveals that the intensity distribution becomes significantly smoother and more spatially homogeneous after defocusing. This enhanced uniformity is more conducive to accurately representing the stable optical properties.

Defocusing tests were subsequently performed on two thin-film samples. The reflectance spectra extracted from the same spatial location were compared against reference measurements from the spectrometer, as shown in Fig. 3. Significant differences between the spectral curves before and after defocusing are observed within the 440–680 nm wavelength range. The spectrum after defocusing aligns much more closely with the spectrometer measurement. The consistent spectral waveform trends confirm that op-

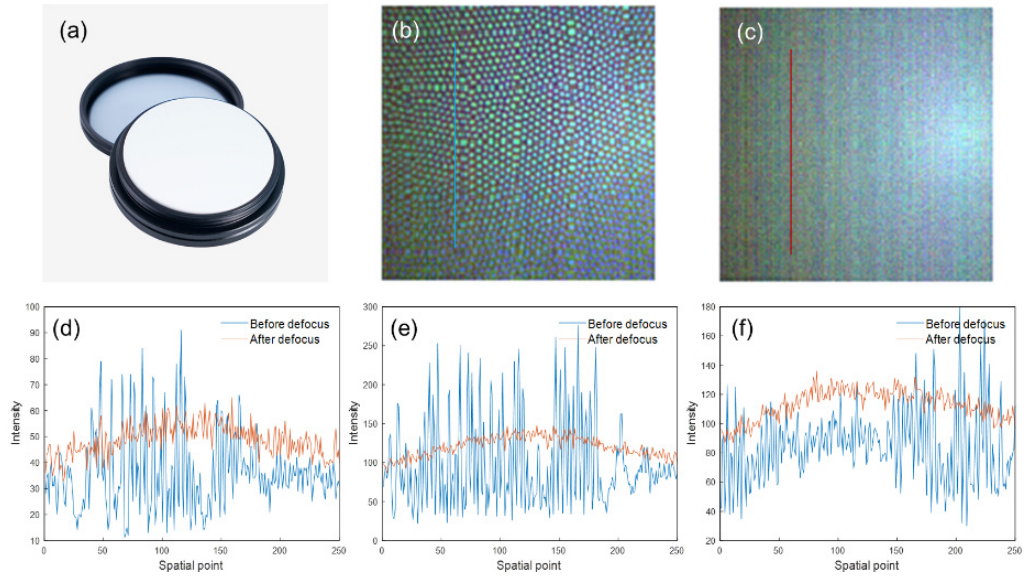


Fig. 2. Comparison of the honeycomb structure before and after defocusing. (a) Diffuse reflection standard whiteboard; (b) whiteboard honeycomb structure image; (c) result after defocusing; (d) intensity images before and after defocusing at 640 nm; (e) intensity images before and after defocusing at 532 nm; (f) intensity images before and after defocusing at 471 nm.

tical defocusing effectively mitigates the imaging artifacts induced by the honeycomb structure while faithfully preserving the sample's intrinsic spectral pattern.

The spectral similarity indices (SAM and RMSE) for both samples before and after defocusing were calculated and are summarized in Table 1. The post-defocusing metric values, both for SAM and RMSE, are relatively low, which further indicates that the reflectance spectra after defocusing exhibit high similarity with the spectrometer measurements and effectively preserve the spectral information of the samples.

3.2. Reflectance calibration of hyperspectral images

To visualize the thin-film samples, different imaging methods were employed, as shown in Fig. 4. Figures 4(a), (e), (i), and (m) present photographs of the four thin-film samples captured using a conventional color camera. Figures 4(b), (f), (j), and (n) show RGB pseudo-color images of localized areas of the four samples acquired with the hyperspectral camera before defocusing. Figures 4(c), (g), (k), and (o) display the corresponding RGB pseudo-color images of the same localized areas after defocusing.

As observed from the results, the image data directly acquired by the endoscopic hyperspectral imaging system includes information from the illumination source. As a result, the pseudo-color images of the samples differ considerably from their photographs, compromising the intuitive visual inspection of the sample surface. By recalculating the hyperspectral data of the thin-film samples after defocusing using Eq. (1)

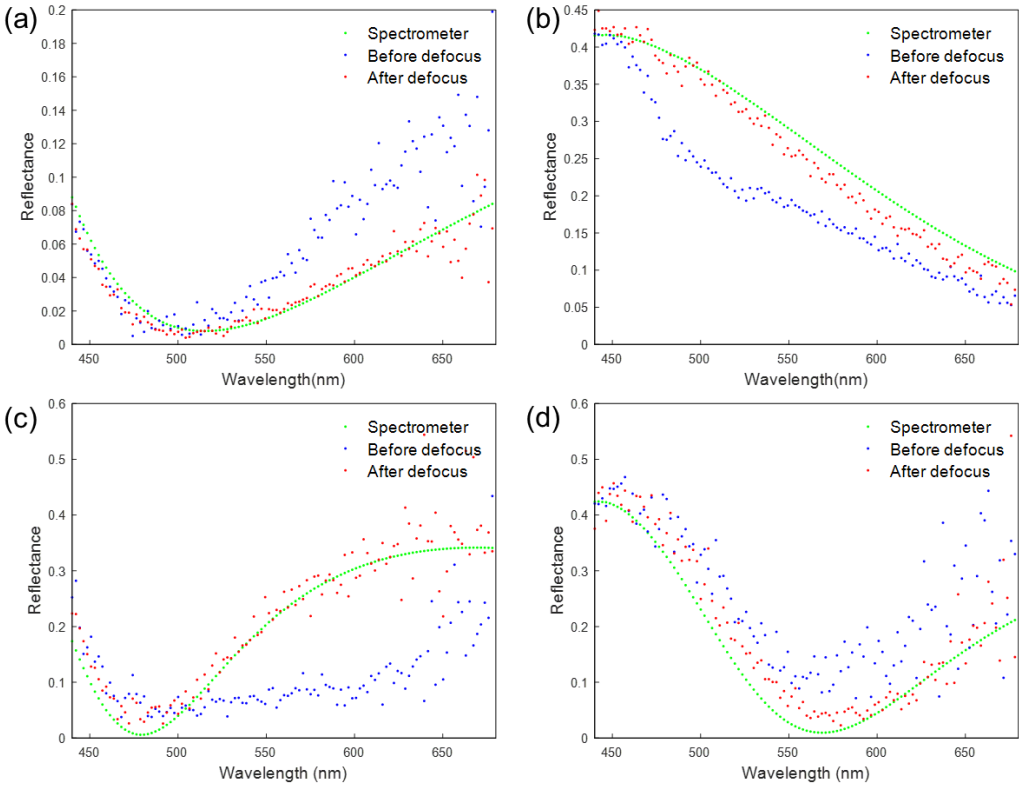


Fig. 3. Spectral comparison of cerium oxide samples before and after defocusing. (a) Spectral diagram of sample 1; (b) spectral diagram of sample 2; (c) spectral diagram of sample 3; (d) spectral diagram of sample 4.

T a b l e 1. Spectral differences of different samples before and after defocusing.

Indexes		Sample 1	Sample 2	Sample 3	Sample 4
SAM	Before defocusing	0.3317	0.1861	0.5419	0.3502
	After defocusing	0.2068	0.0709	0.1694	0.2071
RMSE	Before defocusing	0.0357	0.0857	0.1423	0.1108
	After defocusing	0.0095	0.0240	0.0452	0.0547

T a b l e 2. Image quality of different samples before and after image calibration.

Indexes		Sample 1	Sample 2	Sample 3	Sample 4
PSNR [dB]	Before calibration	10.7877	7.9735	8.1711	6.2947
	After calibration	31.6964	22.4702	23.2379	20.3543
SSIM	Before calibration	0.0567	0.5277	0.3725	0.3115
	After calibration	0.6199	0.9524	0.8980	0.8023

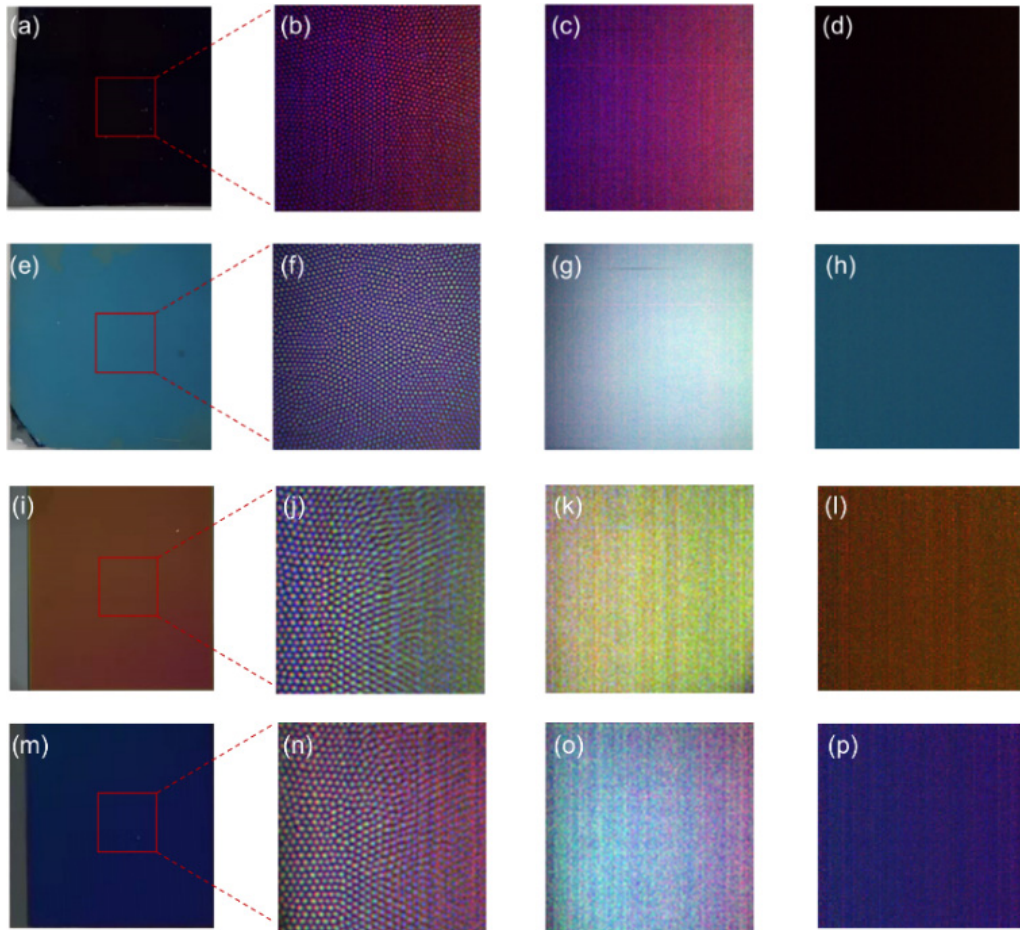


Fig. 4. Comparison of images of cerium oxide samples before and after image calibration. (a) Photograph of sample 1; (b) magnified local image of sample 1 before defocusing; (c) magnified local image of sample 1 after defocusing; (d) magnified local image of sample 1 after defocusing and calibration; (e) photograph of sample 2; (f) magnified local image of sample 2 before defocusing; (g) magnified local image of sample 2 after defocusing; (h) magnified local image of sample 2 after defocusing and calibration; (i) photograph of sample 3; (j) magnified local image of sample 3 before defocusing; (k) magnified local image of sample 3 after defocusing; (l) magnified local image of sample 3 after defocusing and calibration; (m) photograph of sample 4; (n) magnified local image of sample 4 before defocusing; (o) magnified local image of sample 4 after defocusing; (p) magnified local image of sample 4 after defocusing and calibration.

to obtain reflectance data for pseudo-color images, as shown in Figs. 4(d), (h), (l), and (p), it can be seen that the calibrated images not only closely resemble the photographs visually but also exhibit a more uniform surface. This indicates that the influence of the illumination source has been effectively eliminated.

A quantitative evaluation of the imaging quality was performed using PSNR and SSIM metrics, with results listed in Table 2. The reflectance-calibrated images exhibit

higher PSNR values and SSIM indices closer to 1 compared to their uncalibrated counterparts. This confirms the superior image quality of the reflectance-based pseudo-color images and their higher structural similarity to the actual sample photographs.

3.3. Film thickness correction and spatial distribution

Based on the reflectance of the thin-film samples, the film thicknesses before and after incidence angle correction were calculated multiple times through spectrum fitting and compared with the ellipsometry measurements, as shown in Table 3. For sample 1, the thickness derived with correction shows excellent agreement with the ellipsometry measurements. The fitting error is improved from approximately 2.7% to below 1%, demonstrating that incorporating the incident angle significantly enhances fitting accuracy. The film layers of sample 2, sample 3, and sample 4 are thicker than sample 1. Due to the complexity of spectral characteristic information, thicker films carry relatively more information in their reflectance spectra. Consequently, after incidence angle correction, the film thickness obtained from spectrum fitting is closer to that measured by ellipsometry, further improving the accuracy.

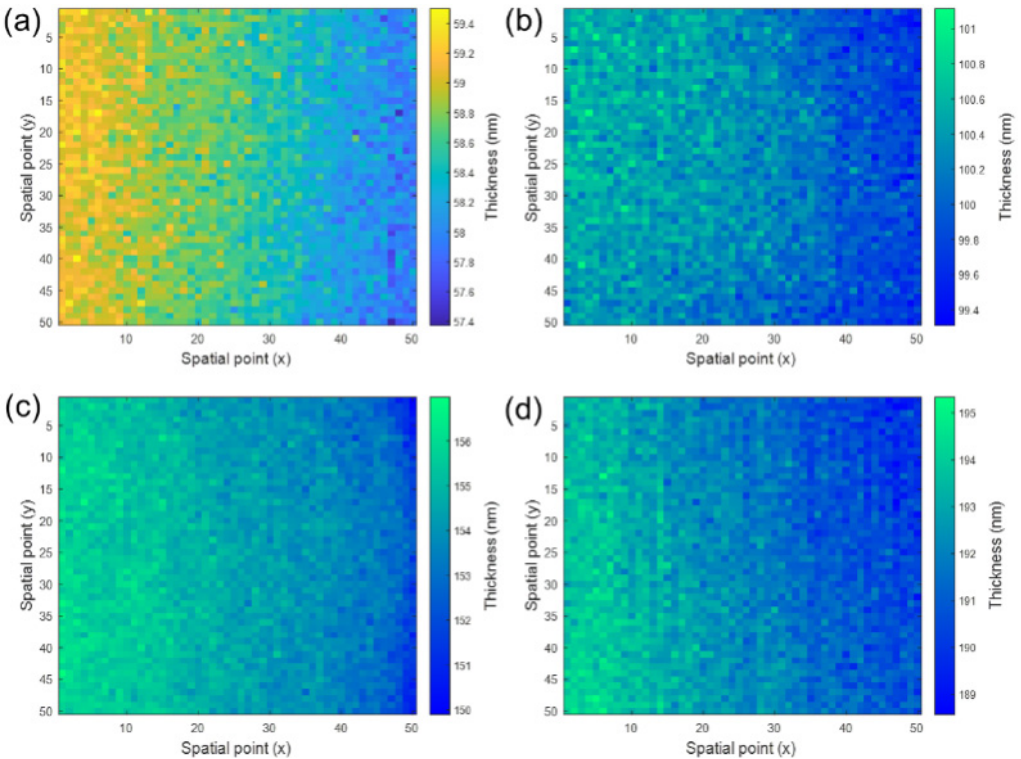


Fig. 5. Distribution of film thickness for different samples. (a) Distribution diagram of film thickness for sample 1; (b) distribution diagram of film thickness for sample 2; (c) distribution diagram of film thickness for sample 3; (d) distribution diagram of film thickness for sample 4.

T a b l e 3. Film thicknesses of different samples before and after incident angle correction.

Thickness type		Sample 1	Sample 2	Sample 3	Sample 4
Ellipsometer [nm]		58.6	102.1	152.8	189.3
Before angle correction	Fitting [nm]	57.0 ± 0.5	98.3 ± 1.2	150.8 ± 0.1	194.8 ± 0.3
	RE	(2.7 ± 0.8)%	(3.7 ± 1.2)%	(1.3 ± 0.0)%	(2.9 ± 0.1)%
After angle correction	Fitting [nm]	58.1 ± 0.3	101.4 ± 0.5	152.6 ± 0.1	189.8 ± 0.1
	RE	(0.9 ± 0.4)%	(0.7 ± 0.5)%	(0.1 ± 0.0)%	(0.3 ± 0.0)%

Furthermore, the thicknesses were calculated point-by-point across the sample surface, accounting for the spatially varying incident angle, to generate the thickness distribution maps shown in Fig. 5. These maps clearly reveal the variation in thickness across the entire surface. Statistical analysis of the film surface distribution shows that sample 1 has an average thickness of approximately 58.6 nm with a surface RSD of 0.7%, and the fitting time for the entire region is 4330 s. Sample 2 exhibits an average thickness of about 100.2 nm and a RSD of 0.3%, with a fitting time of 4125 s. Sample 3 has an average thickness of roughly 154.4 nm, a RSD of 0.7%, and a fitting time of 4285 s. Sample 4 shows an average thickness of approximately 192.1 nm, a RSD of 0.7%, and a fitting time of 3607 s. These results indicate that all four samples exhibit excellent thickness uniformity. However, the fitting process is time-consuming, which limits the efficiency of large-area inspection. This underscores the need for algorithm optimization in future work.

4. Conclusion

To address the challenge of measuring the thickness distribution of the thin films within complex internal structures, this study proposed a novel *in situ* method by integrating fiber optic endoscopy with hyperspectral imaging. Experimental results confirmed that the defocusing technique not only effectively suppressed the honeycomb artifact but also preserved the fidelity of the spectral data. The reflectance hyperspectral images of the thin films more accurately depicted the surface condition, with the SSIM values of some samples approaching 1. After incidence angle correction, the error level of the film thickness obtained from spectrum fitting was reduced from approximately 3% to about 0.5%. Moreover, a more accurate thickness distribution map of the thin film surface was obtained based on the incidence angle correction across the entire field of view. Since the acquired hyperspectral reflectance data contains information across numerous wavelength bands, future work will focus on employing a multispectral camera to streamline the data acquisition and fitting process, thereby improving the efficiency of large-area film thickness analysis.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (12304352).

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*Received January 13, 2026
in revised form February 28, 2026*