High-Performance Ellipsometry With 2-D Expanded Channels for Spectroscopy and Polarization Analysis

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***Abstract*— We constructed and investigated a high-speed broadband spectroscopic ellipsometric system with 12 polarization channels and a 2-D charge-coupled device. The system without any mechanically moving component completes the measurements of more than 10 000 polarization signals at 889 data points in a wavelength range of 400–800 nm within 150 ms, with a spectral resolution better than 1 nm. An integrated analyzer consisting of 12 subanalyzers was employed to obtain the light of different polarization states simultaneously. The spectral distribution of different polarization channels was acquired by the spectral data acquisition system in parallel mode. Two kinds of data processing methods were applied to analyze the light intensities of different channels to obtain the ellipsometric information and other physical parameters of the material over a broad spectral range. According to the analysis of measurement results of gold and silicon bulk, and tantalum pentoxide film, the reliability of the proposed instrument was verified, showing application prospects in the field where *in situ* spectral monitoring is required.**

***Index Terms*— Ellipsometry, high-speed measurement, multiple polarization channels, parallel mode, spectroscopic data acquisition.**

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I. Introduction

Ellipsometry has become a mainstream technique in the investigation of optical properties and surface analyses [1]–[5] with the merits of high measurement sensitivity, high accuracy, noncontact, and nondestructive [6]. In the industrial production and the optical-film preparation, where the process is often *in situ* monitored by the optical methods, the ellipsometry is superior to the ordinary reflection or transmission since it extracts the intensity and the phase change information of light simultaneously. Moreover, ellipsometry is also an extremely useful tool for *in situ* monitoring and characterization [7]–[11]. Accordingly, the high-speed ellipsometers, which complete the data acquisition in a short time, are developed for the accurate measurement.

The ellipsometers using high-frequency modulation devices, such as the liquid crystal variable retarder (LCVR) and the photoelastic modulator (PEM), have shown significant advantages to achieve high-speed measurement. The retardation of LCVR can be either modulated at a low frequency or fixed to enable fast spectroscopic measurements [12]–[14]. The PEM has also shown to be effective as a dynamic retarder with electrically tunable phase retardance based on the photoelastic effect [15]–[17]. Compared with the ellipsometers with high-frequency modulation devices, multichannel ellipsometers are less sensitive to the temperature and the wavelength with a simple and clear physical concept. Moreover, the signals are acquired in parallel mode, which ensures that the ellipsometric information is characterized at the same moment. In our previous work [18], an ellipsometer with an integrated analyzer was presented on the basis of the conventional rotating-analyzer ellipsometry (RAE) [19]–[21] and multichannel configuration [22]–[25]. The ellipsometric parameters were extracted within 1 s without any moving element, achieving a high-speed measurement at a single wavelength. However, the incapability of spectroscopic measurement limits greatly the application of the instrument.

In this work, a type of ellipsometer was theoretically and experimentally investigated to realize the fast measurement of various materials in a broad spectral range. 12 polarization channels were adopted to improve the precision. The dispersion and the data acquisition were completed by only one spectrometer with a 2-D charge coupled device (CCD) detector. The CCD pixels were divided into 12 spectral belts for imaging the relevant polarization channels. Subsequently, the spectral ellipsometric parameters of the sample were obtained by analyzing the intensity information. The measuring time turned out to be 150 ms, which was consumed mainly by the CCD exposure time and the data processing. The ellipsometric system achieved the high-speed measurement of more than 10 000 polarization signals at 889 wavelength points in a spectral range of 400–800 nm without any mechanically moving component, satisfying the increasing demand for rapid ellipsometric measurement in scientific research and industrial fields.

II. Principle

The principle of the developed ellipsometer is mainly based on RAE. An integrated analyzer consisting of 12 subanalyzers with azimuths in a range of 0°–180° replaces the rotating analyzer for the measurement of different polarization states. A light beam from the source goes through a polarizer with a fixed azimuth at 45° and a sample sequentially before entering the integrated analyzer. After eliminating the effect of the background signal, the light intensity can be given by Aspnes and Studna [19]

$$I = I_0 + I_c \cos 2A + I_s \sin 2A \tag{1}$$

where I_0, I_c, and I_s, represent the amplitudes of dc, cosine, and sine components, respectively, and A represents the azimuth of subanalyzer. The ellipsometric parameters can be acquired by applying the intensity fitting method (IFM) on 12 discrete intensities from different polarization channels, which was described in detail in our previous work [18].

To achieve shorter data processing time and higher data accuracy, the matrix calculation method (MCM) was proposed for determining the ellipsometric parameters. According to (1), the light intensity from an individual subanalyzer is expressed as

$$I_i = m_1 + m_2 \cdot \cos 2A_i + m_3 \cdot \sin 2A_i \tag{2}$$

where m_1, m_2, and m_3 are the parameters introduced in data processing. For three discrete channels, the light intensities are expressed as

$$I_1 = m_1 + m_2 \cdot \cos 2A_1 + m_3 \cdot \sin 2A_1 \tag{3}$$

$$I_2 = m_1 + m_2 \cdot \cos 2A_2 + m_3 \cdot \sin 2A_2 \tag{4}$$

$$I_3 = m_1 + m_2 \cdot \cos 2A_3 + m_3 \cdot \sin 2A_3 \tag{5}$$

where A_1, A_2, and A_3 are the azimuths for three subanalyzers. Then these three equations can be rewritten as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 1 & \cos 2A_1 & \sin 2A_1 \\ 1 & \cos 2A_2 & \sin 2A_2 \\ 1 & \cos 2A_3 & \sin 2A_3 \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}. \tag{6}$$

For simplicity, two vectors V, W, and a matrix M are defined by

$$W = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}, \quad M = \begin{bmatrix} 1 & \cos 2A_1 & \sin 2A_1 \\ 1 & \cos 2A_2 & \sin 2A_2 \\ 1 & \cos 2A_3 & \sin 2A_3 \end{bmatrix}, \quad V = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}. \tag{7}$$

Then

$$W = M \cdot V \tag{8}$$

$$V = M^{-1} \cdot W \tag{9}$$

where W is the vector corresponding to the light intensity from the integrated analyzer, and M is related to the azimuths of the subanalyzer group. To reduce the data processing time, M can be calculated precisely in advance as experimental parameters with the calibrated azimuths of subanalyzers. Parameters m_1, m_2, and m_3 can be determined from (9). Then the ellipsometric parameters ψ and Δ, which represent the angle determined from the amplitude ratio and the phase difference between reflected p- and s-polarizations [26], respectively, are obtained as

$$\begin{aligned} \tan\psi &= [(I_0 - I_c)/(I_0 + I_c)]^{1/2} \\ &= [(m_1 - m_2)/(m_1 + m_2)]^{1/2} \end{aligned} \tag{10}$$

$$\begin{aligned} \cos\Delta &= I_s/\left(I_0^2 - I_c^2\right)^{1/2} \\ &= m_3/\left(m_1^2 - m_2^2\right)^{1/2}. \end{aligned} \tag{11}$$

In experiment, due to the discrepancy between the light intensity in space from the source, the reflectance of sample, and the transmittance of each subanalyzer, a uniform factor η is introduced to eliminate the effect on accuracy. For an individual subanalyzer, the light intensity should be modified as

$$I_{ir} = \eta_i \cdot (I_0 + I_c \cos 2A_i + I_s \sin 2A_i) = \eta_i \cdot I_i \tag{12}$$

where η_i represents the uniform factor, I_{ir} is the raw light intensity obtained by the detector, and I_i is the light intensity used in data processing. Then

$$I_i = I_{ir}/\eta_i. \tag{13}$$

The uniform factor for each subanalyzer is determined with the calibration method described in [18]. By applying the same method to each single wavelength point, the spectra of ellipsometric parameters are obtained in the working spectral range within a short time.

III. Experiment

The schematic and the measurement setup photograph of the developed ellipsometer are shown in Figs. 1 and 2, respectively. The system consists of a light source, a rotating stage, a spectrum acquisition system, and a computer control system. A light beam from the continuous radiation source goes through the polarizer with a fixed azimuth after collimation before oblique incidence on the sample. The reflected light

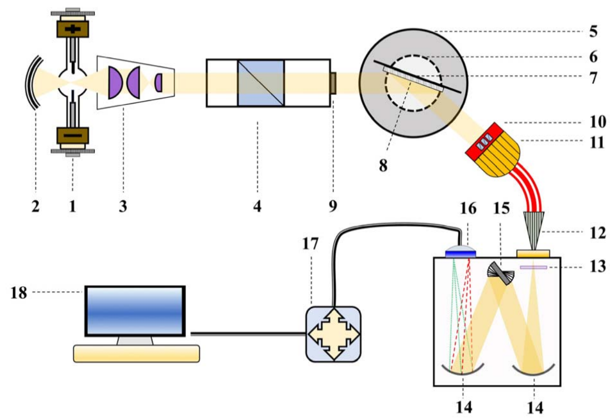

Fig. 1. Schematic of the designed ellipsometric system. 1: continuous light source. 2: spherical mirror. 3: light-collimating lens. 4: fixed polarizer. 5: rotating stage. 6: sample rotator. 7: sample holder. 8: sample. 9: incident window. 10: integrated analyzer. 11: fiber-coupler array. 12: optical-fiber adapter. 13: filter. 14: spherical mirrors. 15: plane grating. 16: 2-D CCD detector. 17: controller. 18: computer.

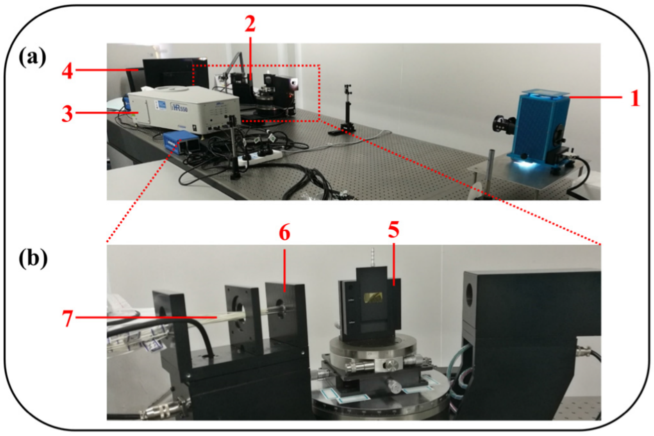

Fig. 2. (a) Photograph of the configuration of system. 1: light source. 2: ellipsometric rotating system. 3: spectrum acquisition system. 4: computer control system. (b) Enlarged photograph of the ellipsometric rotating system. 5: sample stage. 6: integrated analyzer. 7: fiber-coupler array.

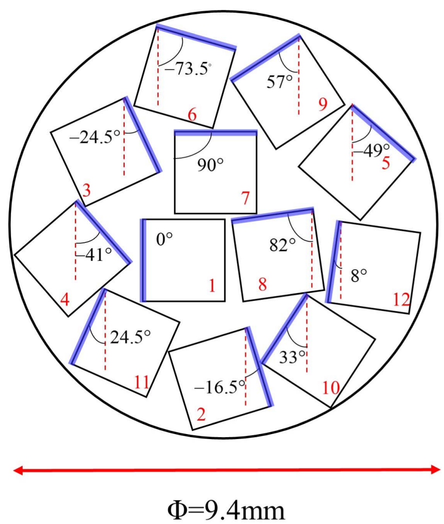

Fig. 3. Schematic of the 12 subanalyzers designed in a dimension of 9.4 mm.

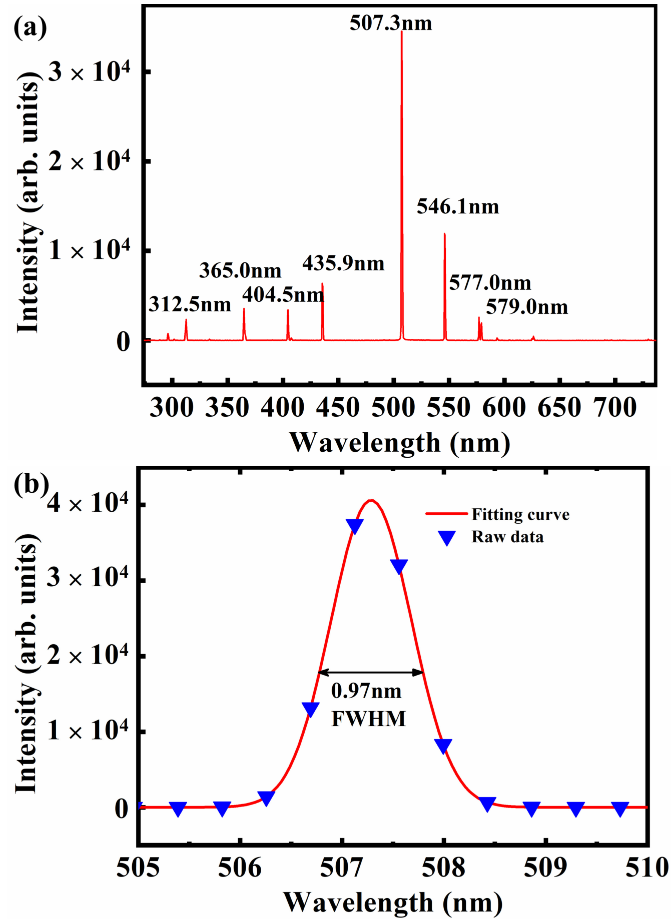

Fig. 4. (a) Spectral lines of mercury lamp measured by the spectrometer. (b) Magnified view of the well-resolved spectral line and the fitting curve at 507.3 nm.

enters the integrated analyzer and passes through 12 channels carrying information of different polarization states. A high-pass filter with a wavelength-cut edge at 400 nm is employed to block higher-order diffraction light. The plane grating is used for dispersion to image the spectra of different channels on the focal plane precisely. The CCD detector is connected to a computer control system, which converts the light-intensity information from analog to digital signals and completes the data acquisition process. The experimental devices are firmly fixed on the optical vibration isolation platform.

The designed integrated analyzer consists of 12 identical subanalyzers, each of which is a Glan Thompson prism, with a transmission window size of 1.5 mm $\times$ 1.5 mm and an extinction ratio of 10^5. The 12 subanalyzers are embedded in a plane containing 12 tiny square holes, the azimuths of which are designed to be arranged in 0°–180°, as shown in Fig. 3. After passing through the corresponding fiber-coupling channels, light is rearranged by an optical fiber adapter along the direction perpendicular to the incident plane before entering the spectrum acquisition system.

A HORIBA-iHR fully automated imaging spectrometer was used as the spectral measurement system. The spectrometer employed a traditional Czerny-Turner structure, which contained a long-pass filter, two spherical mirrors, a plane grating, and a CCD detector. The grating, with a groove density of 100 lines/mm and a blaze wavelength of 450 nm, was used for dispersion. The horizontal dimension of CCD imaging was 26.7 mm, with 1024 $\times$ 256 pixels in the horizontal and the vertical directions, respectively. The position and the angle of grating were fixed precisely to obtain the images of 12 independent optical channels in a spectral range of 400–800 nm simultaneously.

The spectrometer was first calibrated with a mercury lamp before application. The mercury lamp spectrum recorded by the spectrometer is shown in Fig. 4(a). The spectrum indicates that each peak of the mercury lamp can be resolved clearly with no ambiguity. By fitting the spectral peak at 507.3 nm, the full width at half maximum (FWHM) was evaluated in Fig. 4(b). The result demonstrates that the value of spectral resolution is 0.97 nm.

The spectral-data acquisition system collects the spectral intensity information of the 12 polarization channels independently. The extinction effect of subanalyzers with different

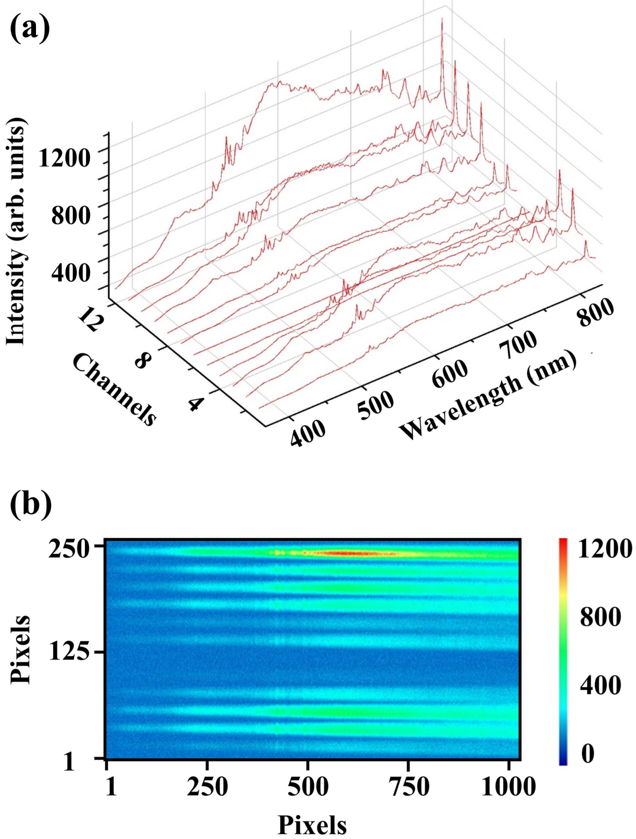

Fig. 5. (a) Spectra of 12 polarization channels for Au bulk, measured at an incident angle of 70°. (b) Corresponding image pattern for the spectra showing the distribution of light intensity for 12 optical channels.

azimuths leads to significant discrepancies in light intensity as indicated in Fig. 5(a). The CCD pixels are divided into 12 spectral belts to image the corresponding spectrum of each polarization channel separately. In Fig. 5(b), the 12 stripe lines from top to bottom correspond to different polarization channels, respectively.

Au was selected as the calibration material for the suggested instrument, due to the great stability of optical properties in the atmospheric environment with a low penetration depth in the visible range. The incident angle was set to be 70° for being close to the principal angle in the spectral region and for an adequate reflection intensity. The polarizer azimuth was calibrated with a self-developed differential spectral analysis method [27]. The optical alignment was performed elaborately by the method presented in [28], with a precision better than 0.01°.

To obtain the real azimuths of 12 subanalyzers precisely, the incident angle was set at 90° in calibration. The light beam from the polarizer entered directly into the integrated analyzer without the reflection of the sample. According to Malus's law, the light intensity from an individual subanalyzer is written as

$$I_i(P) = I_0(P) \cdot \frac{1}{2}[1 + \cos 2(P - A_i)] \tag{14}$$

where P and A_i represent the azimuths of polarizer and subanalyzer, respectively. $I_0(P)$ is the intensity of light from the polarizer with the azimuth of P. By rotating the precisely calibrated polarizer, the variation of the light intensity from each subanalyzer was obtained in parallel. The values of subanalyzer azimuths were determined precisely by fitting the data of light intensity into a cosine form. The calibration results at each wavelength point in the spectral range are exhibited in Fig. 6. The real azimuths of 12 subanalyzers are listed in Table I.

TABLE I
CALIBRATED AZIMUTH FOR EACH SUBANALYZER

No. of sub-analyzer	Actual azimuths (°)
1	179.85
2	161.89
3	151.36
4	131.68
5	113.40
6	104.15
7	89.35
8	79.57
9	59.38
10	42.21
11	29.33
12	9.44

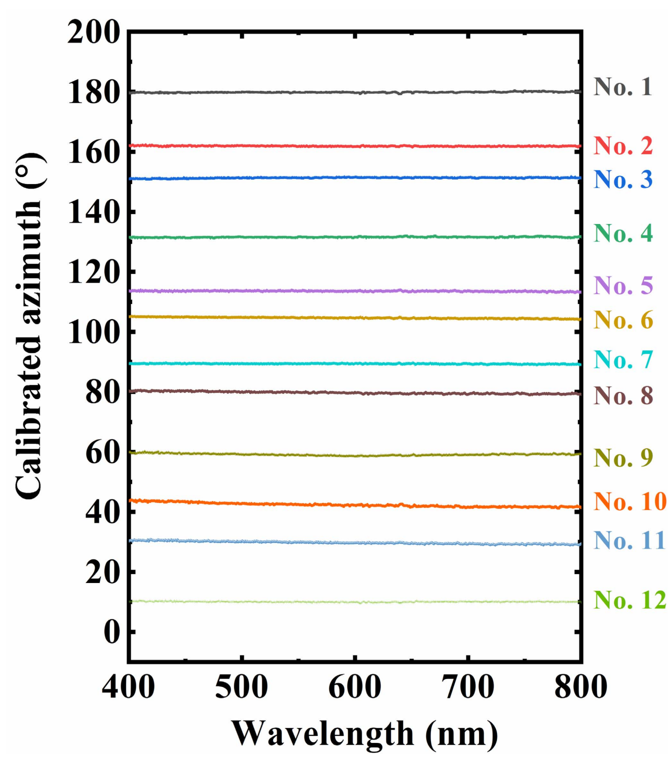

Fig. 6. Calibration results of subanalyzers at each wavelength point in a spectral range of 400–800 nm.

IV. RESULTS AND DISCUSSION

In the measurement, the light intensities from 12 channels at an incident angle of 70° were fit into cosine form at each

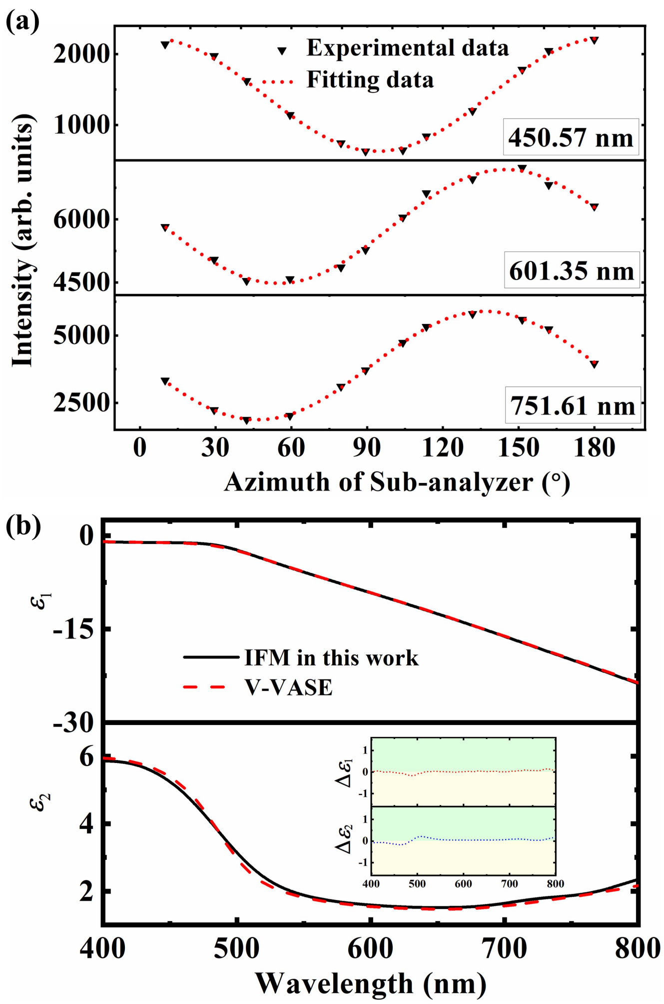

Fig. 7. (a) Comparison between 12 raw data of light intensity and fitting curves at three typical wavelengths in the spectral range. (b) Dielectric functions of the Au bulk sample measured with the developed ellipsometer in this work and the V-VASE (J. A. Woollam), with the differences shown in the inset.

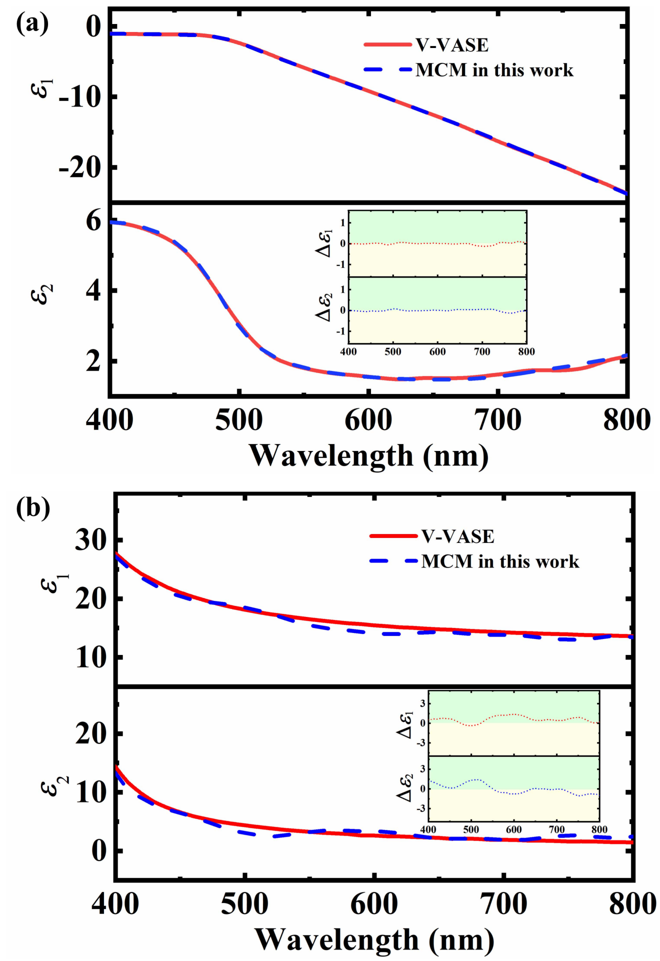

Fig. 8. Measured dielectric functions at an incident angle of 70° of the (a) Au and (b) Si bulk samples, compared with those with the V-VASE (J. A. Woollam), with the differences shown in the insets.

TABLE II

Comparison of the Measuring Time and the Measured Wavelength Points Between This Work and Other Self-Established Ellipsometers

Method	Wavelength points	Measuring time
IFM in this work	889	5 s
MCM in this work	889	150 ms
Ellipsometer in [18]	1	1 s
RPAE [28,29]	40	12 min

wavelength point in the spectral range by applying the IFM. The light intensities of 12 channels and their fitting curves are coincident at three typical wavelengths of 450.57, 601.35, and 751.61 nm [Fig. 7(a)].

The dielectric function of Au was calculated subsequently from ellipsometric parameters. The reliability of the result was confirmed by the measured one with the vertical-variable angle spectroscopic ellipsometer (V-VASE) (J. A. Woollam). The comparison of the two results shows good agreement as shown in Fig. 7(b), where ε_1 and ε_2 represent the real and the imaginary parts of dielectric function ε, respectively. The measurement process for 889 wavelength data points in a range of 400–800 nm was completed within 5 s.

Another data processing method MCM was applied to analyze the spectral intensities of multiple channels. The 12 polarization channels were divided into different groups to obtain the ellipsometric parameters according to (2)–(11). The exposure time of CCD was set to be 100 ms in experiment. The analysis program was self-compiled in MATLAB 2016a, with a recorded data processing time of 50 ms. Consequently, the total measurement time of all 889 data points in the spectral range by MCM was 150 ms. The measurement time can be reduced significantly by employing a light source of stronger intensity, a higher-sensitivity CCD, and a higher-performance computer. The properties of two data analysis methods are given in Table II, compared with that of the ellipsometric measurement methods proposed previously by our group.

Au and Si bulk samples were employed to confirm the reliability and the accuracy of the suggested ellipsometer. The

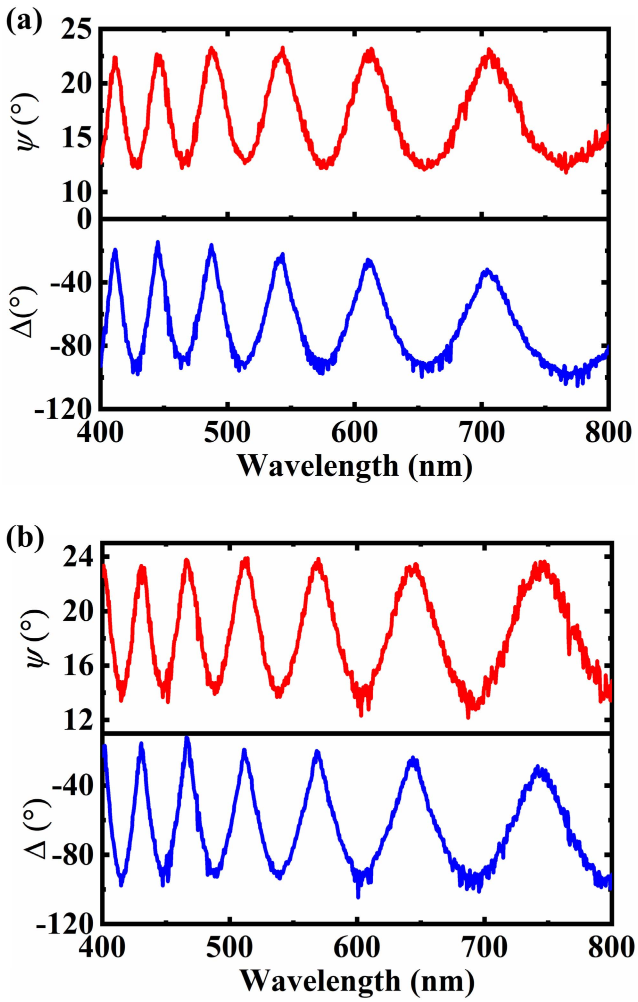

Fig. 9. Ellipsometric parameters of tantalum-pentoxide film prepared on a glass substrate, measured at an incident angle of 70° in the 400–800 nm wavelength range with the suggested ellipsometer. (a) Before and (b) after heating.

measurements were performed at an incident angle of 70°. The dielectric functions were obtained by applying the MCM to the spectral data after eliminating the uniform factors. Our experimental results and those with the V-VASE reveal good agreement (Fig. 8).

The ellipsometric parameters of tantalum-pentoxide film prepared on a glass substrate were obtained before and after heating, as shown in Fig. 9(a) and (b), respectively. The peaks of curves can be clearly distinguished in the spectra. The sample annealed at 400 °C for 3 h showed more peaks in the spectral range, with a smaller distance between adjacent peak positions. This implied that the compressive stress increased in the heated sample, resulting in a thicker or denser film [30]. Consequently, the enhanced refractive index induced the increase of the total optical path, leading to the change of peaks in the spectral range.

V. Conclusion

In summary, a high-performance spectroscopic ellipsometer with 12 polarization channels has been constructed and studied in this work. The system employed an integrated analyzer composed of 12 subanalyzers to realize different polarization channels. A spectrometer with a 2-D CCD detector was used for dispersion and data acquisition in parallel without a mechanically moving component. More than 10 000 polarization signals at 889 wavelength points were obtained simultaneously within 150 ms in a spectral range of 400–800 nm, with a resolution better than 1 nm. The measured dielectric functions of Au and Si bulk samples agreed with those measured with V-VASE (J. A. Woollam), which confirmed the reliability of the developed ellipsometer. Apart from the RAE, the designed configuration with an integrated polarizing element and a spectrometer is also appliable for other rotating-element ellipsometers. This proposed high-speed broadband spectroscopic ellipsometer presents good application prospects in industrial and scientific research fields where real-time spectral measurement with high precision is required.

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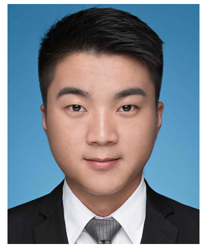

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