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# Wide angle ellipsometry for measuring the optical properties of a metal

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***Abstract:***
*Spectroscopic ellipsometer is the most precise method for characterization the optical and polarizing properties of anisotropic samples. Wide angle of incidence ellipsometer is provides high contrast images for accurate characterization of the ellipsometric parameters of materials. Here we propose rotating compensator ellipsometer* $PSC_RA$ *for the measurement of the ellipsometric parameters. A collimated linearly polarized beam of diameter 30 mm is used for two-dimensional optical constants measurements of the surface. This ellipsometric method is introduced in conjunction with parabolic mirror for measuring the optical constants of a metal at wide angle of incidence simultaneously. Five intensity images at different azimuth angles of the rotating compensator are recorded by CCD camera and analyzed. The information extracted from the detected images is used to determine the dielectric properties of Cadmium sample at angles of incidence range from 43º-83º. The results obtained by the proposed technique is consistent with measured results by null ellipsometry method.*

***Keywords****: Rotating compensator ellipsometer, wide angle of incidence; Dielectric constants.*

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## I. Introduction

Ellipsometry is an optical noncontact technique used for investigation of the optical properties of a material [1, 2]. It measures the change of polarization state of linearly polarized light occurred upon reflection from the surface of the test sample [3, 4]. The optical measurements such as dielectric properties, layer thickness and surface roughness of a material can be extracted from the ellipsometric angles $\Delta, \Psi$ which describes the change in phase and amplitude of the polarization states upon reflection from the test surface [5, 6]. Rotating compensator ellipsometer in conjunction with the capability of linearly polarized light incident on the surface under test at wide angle of incidence instantaneously provides more precise and high contrast imaging for surface and optical metrology measurements. Imaging ellipsometry combines both of the spectroscopic ellipsometer and microscopy which permits characterization of the optical parameter variation of the surface on a microscopic scale [7].

Among the developed wide angle of incidence imaging ellipsometer techniques are non-collimated beam [8] and extended source for illumination [9]. Other techniques based on measuring the lateral distribution of surface by mechanical scanning techniques which are time-consuming work particularly if the surface is of large area [10].

In this paper, a developed rotating compensator ellipsometer system that measures wide angles of incidence instantaneously using parabolic mirror is presented. This technique enables measuring the dielectric constants and the ellipsometric parameters of samples at wide angles of incidence 43º-83º instantaneously. This system depends on the measured technique $PSC_RA$ (rotating compensator ellipsometer) that has more advantages than rotating analyzer or rotating polarizer techniques, it can provide accurate measurements of degree of polarization, small ellipticity angles, phase shift $\Delta$ near 0º or 180º and the sign of the ellipticity of the reflected beam [11, 12]. The samples are also measured using null ellipsometric system to compare it with the results of our developed method.

## II. Experimental work

The optical arrangement of the developed wide-angle technique is described in Figure 1 where He-Ne laser beam of 632.9 nm passes through a polarizer which is adjusted with azimuth angle 45º. A linearly polarized beam of diameter 30 mm collimated via a beam expander is incident on a parabolic mirror. The focused beam is reflected on a sample surface at wide angles of incidence range from 43º-83º and then reflected back to the parabolic mirror. The beam is then reflected to the other arm of the setup which contains a convex lens L to reduce the beam diameter, a quarter wave plate Q which rotates to different azimuth angles and analyzer with fixed azimuth angle 0º. The intensity images are recorded by CCD camera. The sample is fixed on a rotating stage to an angle 0º corresponding to the incident beam. Before starting measurement, the polarizer and analyzer angles are calibrated using the calibration method in [13]. The retardance of the quarter wave plate is calibrated using method represented in [14]. The uncertainty for calibration of its azimuth angle is calculated to be 0.1º.

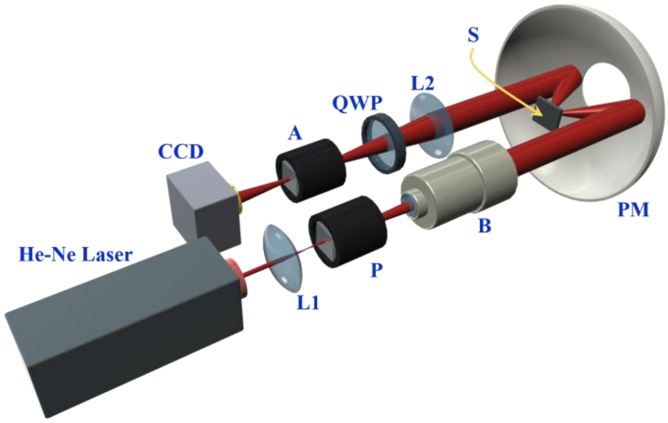


Fig. 1 The optical arrangement of the developed wide angle of incidence ellipsometric setup which consists of: He-Ne Laser at 633 nm; L1, L2: two convex lenses; P, A: Glan-Thompson polarizer and analyzer; B: beam expander; PM: parabolic mirror; S: sample; QWP: quarter wave plate; CCD: CMOS camera.

The fundamental equation of ellipsometry which measures the optical properties of a material based on the analysis of the change occurred in p and s polarization states of the reflected beam is as follows [15]:

$$\rho = \tan \Psi e^{i\Delta} = r_p / r_s \tag{1}$$

where $\tan \Psi$ and $\Delta$ are the measurements of the change occurred in amplitude ratio and phase respectively, $r_p, r_s$ are p and s reflection coefficients of the beam from the surface. The intensity images detected by CCD camera are analyzed by MATLAB software to determine the change in amplitude and phase $\Psi, \Delta$ [16].
In order to measure the ellipsometric parameters, the polarizer P is adjusted at azimuth angle 45, analyzer A is in the plane of incidence (0°) and the compensator is rotated by angle θ. The intensity of the incident light on the CCD camera is predicted as follows [17]:

$$I(\theta) = A_0 + A_2 \cos 2\theta + B_2 \sin 2\theta + A_4 \cos 4\theta + B_4 \sin 4\theta \tag{2}$$

where $A_0$, $A_2$, $B_2$, $A_4$, $B_4$ are the Fourier coefficients, in the case of P & A setting above it can be stated as follows:

$$\begin{aligned} A_0 &= 2 - \cos 2\Psi \\ A_2 &= 0 \\ B_2 &= 2 \sin 2\theta \sin \Delta \\ A_4 &= -\cos 2\Psi \\ B_4 &= \sin 2\Psi \cos \Delta \end{aligned} \tag{3}$$

Five intensity images $I_0$, $I_1$, $I_2$, $I_3$, $I_4$ are captured by adjusting the quarter wave plate at angles 0, π/8, π/4, 3π/8, 3π/4 and the intensity for each angle is as considered as in Eq. 2 [18]. From the intensity values, distribution of the ellipsometric parameters can be determined from the following relations:

$$\Delta = tan^{-1}\left[\frac{I_2 - I_4}{2(I_1 - I_3)}\right] \tag{4}$$

$$\Psi = tan^{-1}\left[\sqrt{\frac{I_0}{I_2 + I_4 - I_0}}\right] \tag{5}$$

The range of angles of incidence is calculated mathematically by means of the beam diameter (30 mm) which is incident on the parabolic mirror surface. The five intensities images are recorded by using CCD camera which has sensing area of 1024×1280 pixels [19]. The captured images are analyzed by pixel/angle of incidence relation for calculation of ellipsometric parameters Ψ, Δ which are measured in its full dynamic range Ψ (0, π/2) and Δ (0, 2π) and this is why RCE technique is preferred [18].
From the ellipsometric parameters, the optical constants of metal can be extracted from [20],

$$n^2(1-k^2) = \sin^2\phi_i\left[1+\frac{\tan^2\phi_i(\cos^2 2\Psi - \sin^2 2\Psi \sin^2\Delta)}{(1+\sin 2\Psi\cos\Delta)^2}\right]$$
$$2n^2k = \frac{\sin^2\phi_i \tan^2\phi_i \sin 4\Psi \sin\Delta}{(1+\sin 2\Psi\cos\Delta)^2} \qquad (6)$$

where $\phi_i$ is the angle of incidence in the surface of the studied metal. The rotating compensator ellipsometry method is preferred than other ellipsometric methods such as rotating analyzer and rotating polarizer ellipsometers in which it provides accurate measurements of the phase shift in the whole range 0º-180º even near 0º or 180º, it can measure the small polarization ellipticity and determine the sign of the ellipticity for the reflected beam after the sample and it can provide all four stokes vector components of the reflected polarized light [13, 14]. To check the results of the ellipsometric parameters and the dielectric properties of the proposed optical setup, the same sample is measured by the null ellipsometric method.

## III. Results and discussion

Measurements are performed using both of the proposed method (as represented in Fig. 1) and null ellipsometric method. The measurements by the ellipsometer were performed at single wavelength of 632.9 nm and different angles of incidence range from 45°-85° in steps of 5. Fig. 2 shows the ellipsometric parameters $\Psi, \Delta$ of Cadmium sample at different angles of incidence. Figures 3 represents the dielectric constants n, k for Cd sample at different angles of incidence using the proposed method and null method.

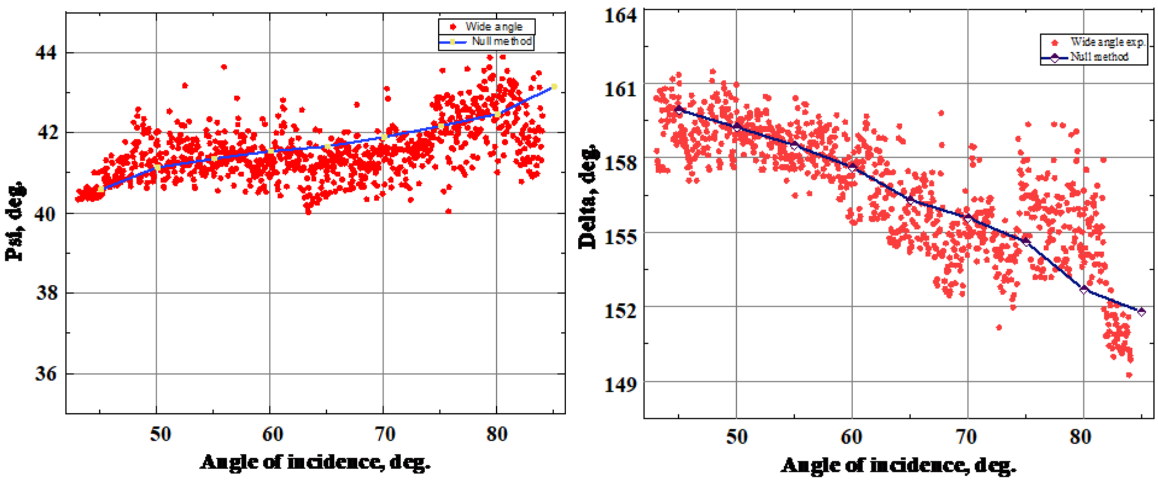


Fig.2. The ellipsometric parameters Ψ, $\Delta$ at different angles of incidence for cadmium sample by wide angle experiment and null ellipsometric method.

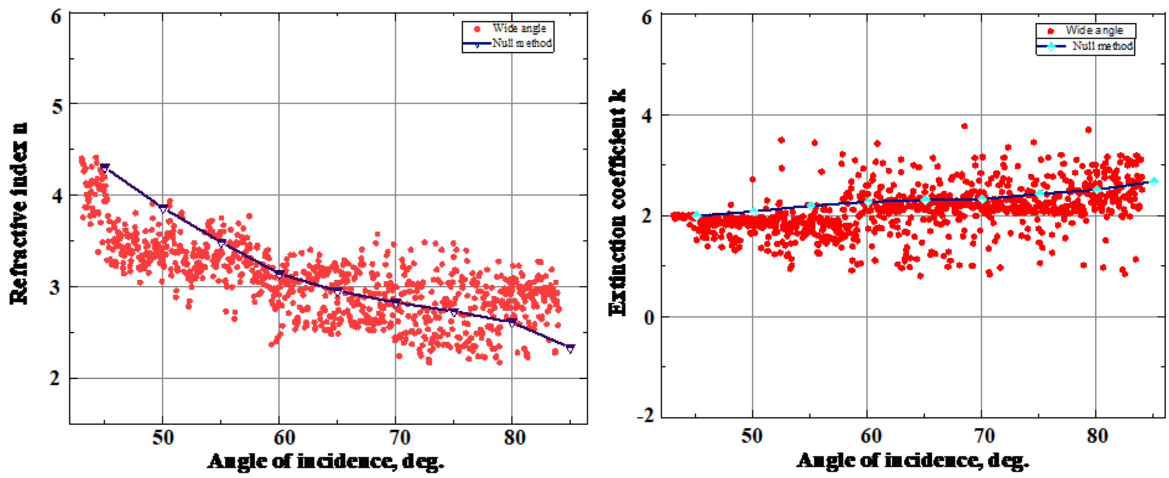


Fig. 3. The optical constants n, k at different angle of incidence for Cd sample measured by wide angle experiment and null ellipsometric method.

Since the measurements are relative values, phase shift perturbation which comes from the parabolic mirror reflections at wide angles of incidence is considered as negligible [22, 23]. Wide angle method has the advantages of time saving since it is a single shot measurement of all angles of incidence for each compensator angle setting [24].

The main sources of uncertainty in n, k, for the wide angle of incidence experiment, are the repeatability, laser wavelength, polarizer, analyzer and Quarter wave plate. The frequency stability of stabilized He-Ne laser is ±5MHz. This corresponds to uncertainty $\pm 3.8\times 10^{-6}$ ° in Δ which is very small with respect to other sources of errors. Repeatability measurement by taking 5 images of the same angle setting of the compensator has uncertainty ± 0.031 for n and ± 0.069 for k. Errors in polarizer and analyzer settings are corrected before starting the experiment. The uncertainty in the wave plate angle setting is ±0.1° that is corresponding to uncertainty ±0.014 in n and ±0.042 in k.

The combined uncertainty in *n* (refractive index) and *k* (extinction coefficient) are as follows:

$$U_n(Cd) = \sqrt{((0.031)^2 + (0.014)^2)}$$

$$U_k(Cd) = \sqrt{((0.069)^2 + (0.042)^2)} \qquad (7)$$

The expanded uncertainty, is equal to the combined uncertainty multiplied by a coverage factor of 2 which refers to a confidence level of 95%. The expanded uncertainty is equal ±0.068 for *n* and ±0.162 for *k*. The uncertainty budget of the calibration system is calculated according to the standard ISO98-3 (2008) [25].

## IV. Conclusion

In conclusion, the optical constants of Cadmium sample are determined using a developed wide angles of incidence ellipsometry method. The ellipsometric parameters are determined at wide angles of incidence range from 43º -83º using rotating compensator ellipsometric method in conjunction with a parabolic mirror. The images captured by CCD camera are analyzed to get the ellipsometric parameters and the optical constants distribution at wide angles of incidence instantaneously of the measured sample. The expanded uncertainty for Cadmium is ±0.068 for n and ±0.162 for k. This method has the advantage of avoiding the probable misalignment caused by the mechanical adjustment of these angles during measurements and also it is considered as time saving method compared with other methods. The same sample is measured using null ellipsometric method and results are found to be in a good consistent with that of the wide-angle method which confirming its accurate performance.

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